High Energy Physics: beyond the LHC

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on the nature of EW symmetry breaking

- EW and strong interactions have free parameters (the symmetry groups, the strength of couplings, the charges of elementary particles). But at least we do have a deep understanding of their dynamical nature, namely the gauge principle. This allows us to speculate about an even deeper origin, e.g. from string theory or higher-dimensional Kaluza-Klein theories

- The Higgs mechanism relies of the quartic Higgs potential, in particular on the negative sign of its quadratic component. But we have no clue as to what is its dynamical origin, independently of whether we look at it with a SM or BSM perspective …

- Understanding the origin of the Higgs potential and the nature of Higgs interactions is a paramount puzzle of modern physics, regardless of whether they eventually match the SM assumption or require new physics

- Having established the existence of the Higgs is similar to having established inflation, through cosmological observations. The real question (for both Higgs and inflation) is now "**where does it come from?**"

a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

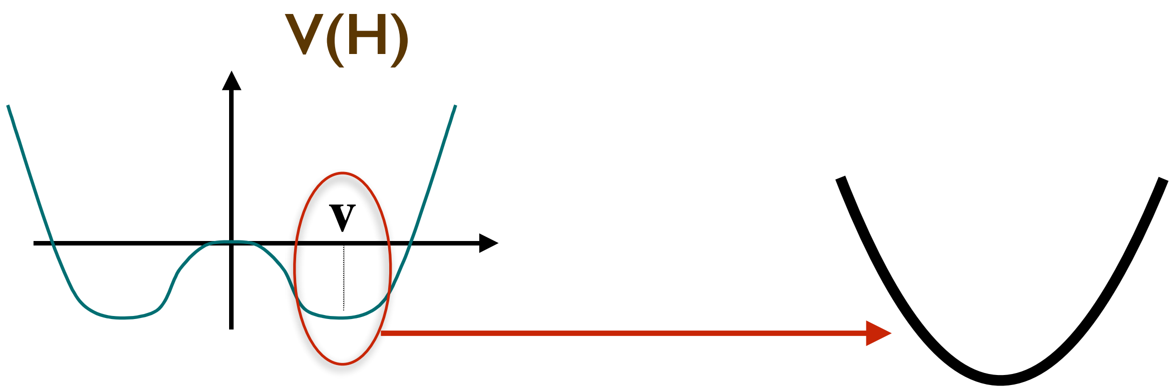
The other *big* questions that press us to look *beyond* the Standard Model

- What's the real origin of EW symmetry breaking and particle's masses?
- What's the origin of Dark matter / energy ?
- What's the origin of matter/antimatter asymmetry in the universe?
- What's the origin of neutrino masses?
- What protects the smallness of m_H / $m_{Plank,GUT}$ (hierarchy problem)?
- ...

- The hierarchy problem, and the search for a ***natural*** explanation of the separation between the EW and Planck scales, provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.
- Lack of experimental evidence, so far, for a straightforward answer to naturalness (eg SUSY), forces us to review our biases, and to **take a closer look even at the most basic assumptions about Higgs** properties
- We often ask "is the Higgs like in SM?" ....The right way to set the issue is rather, more humbly, **"what is the Higgs?"** ...
  - in this perspective, even innocent questions like whether the Higgs gives mass also to 1st and 2nd generation fermions call for experimental verification.

How far have we tested the Higgs mechanism?

parameters of the potential

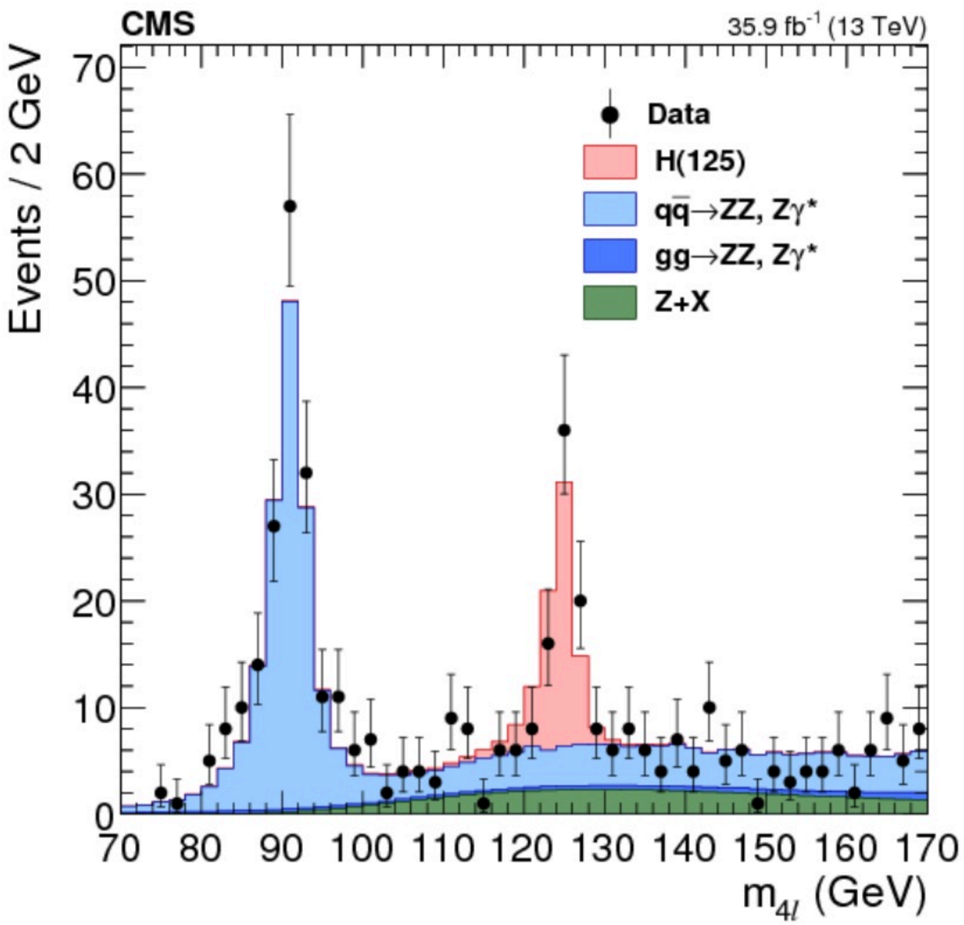


$V(H) \sim m_H^2\,(H-\mathbf{v})^2$

v=246 GeV, from weak decays

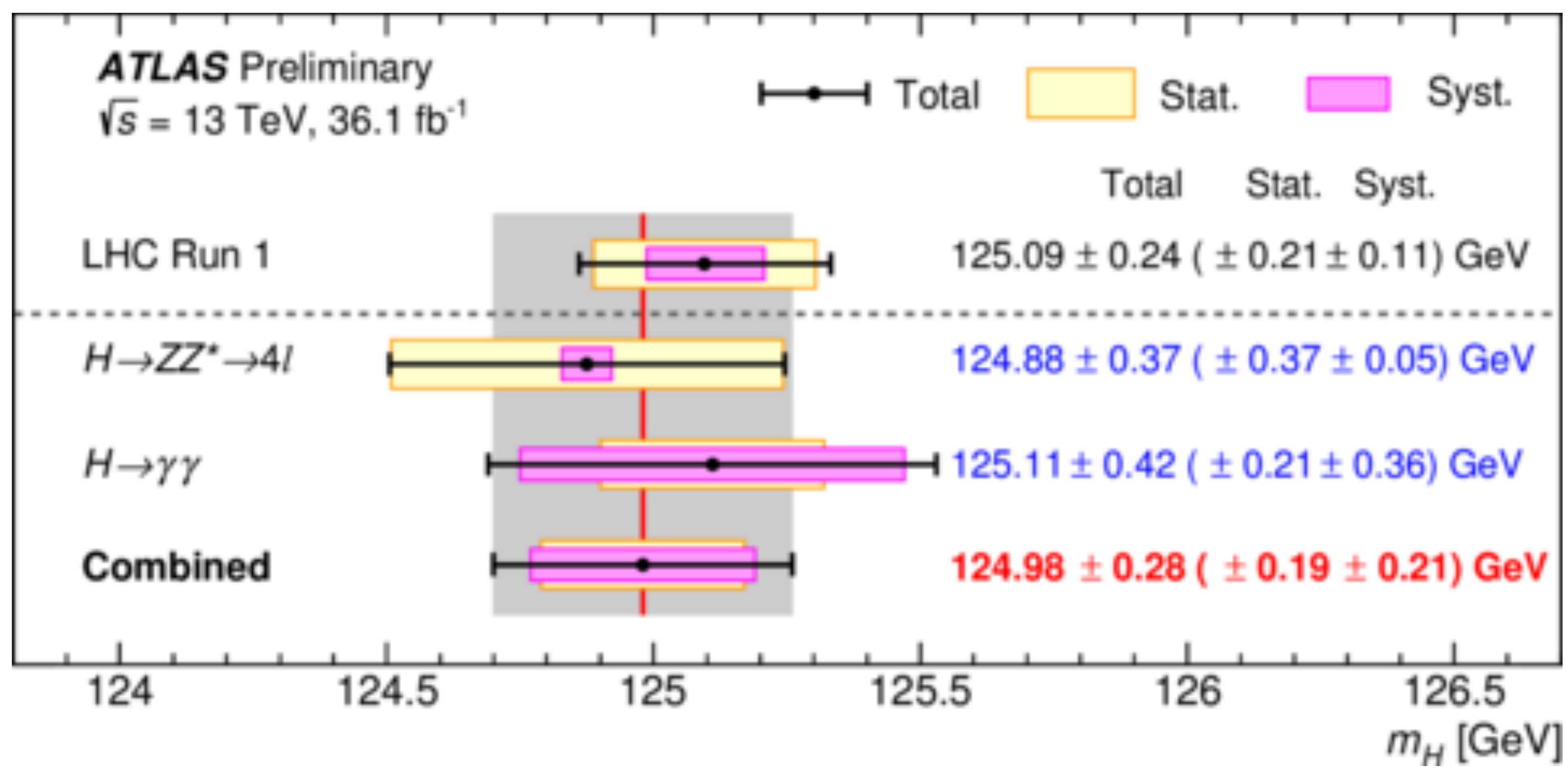
Higgs mass, 2017

CMS



arXiv:1706.09936

ATLAS



ATLAS-CONF-2017-046

3D likelihood fit (m_{4l}, ZZ bg, δm) ⇒

$m_H = 125.26 \pm 0.20_{stat} \pm 0.08_{syst}$ GeV

$= 125.26 \pm 0.22$ GeV

γγ and 4ℓ combination, run 1+2 ⇒

$m_H = 124.98 \pm 0.19_{stat} \pm 0.21_{syst}$ GeV

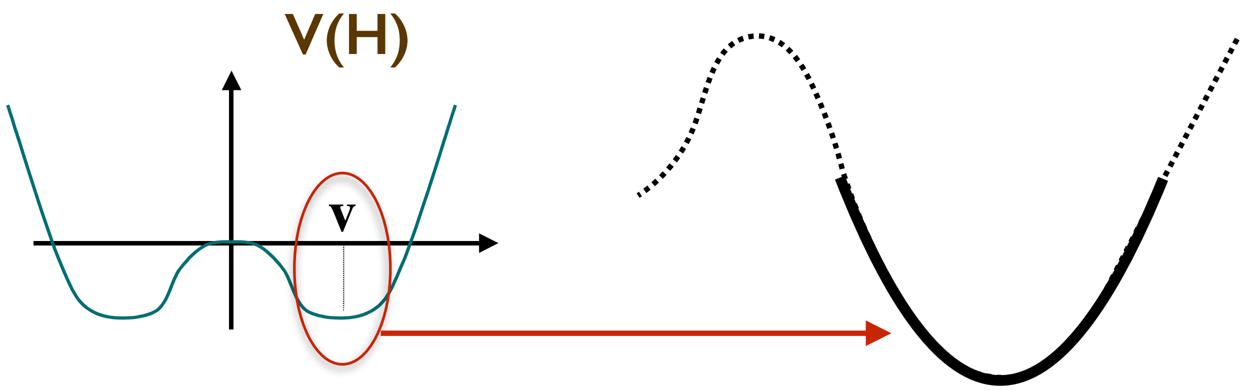
$= 124.98 \pm 0.26$ GeV

⇒ 2 x 10^{-3} precision ….

it took over 6 years from 1983 discovery to get below 5 x 10^{-3} on m_Z (1989: CDF, SLC, LEP)

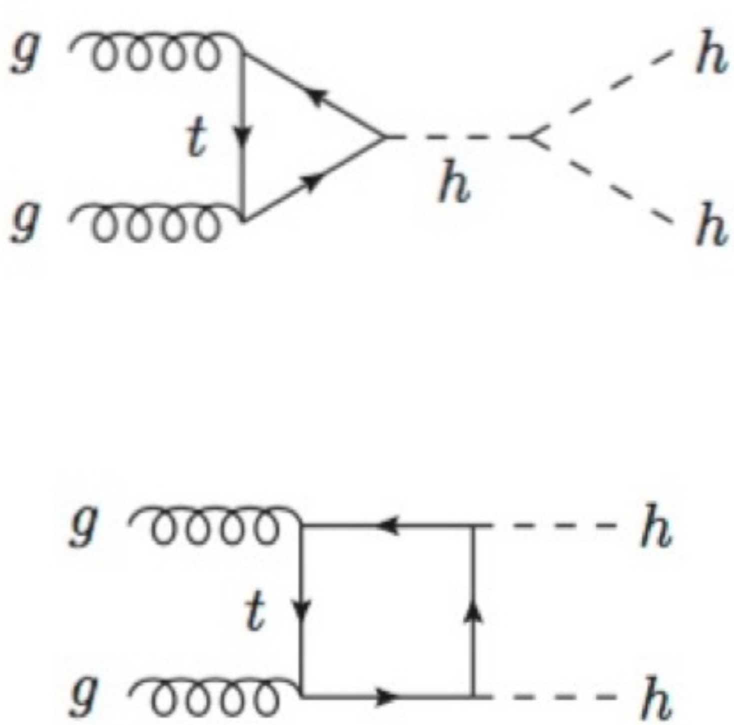
How far have we tested the Higgs mechanism?

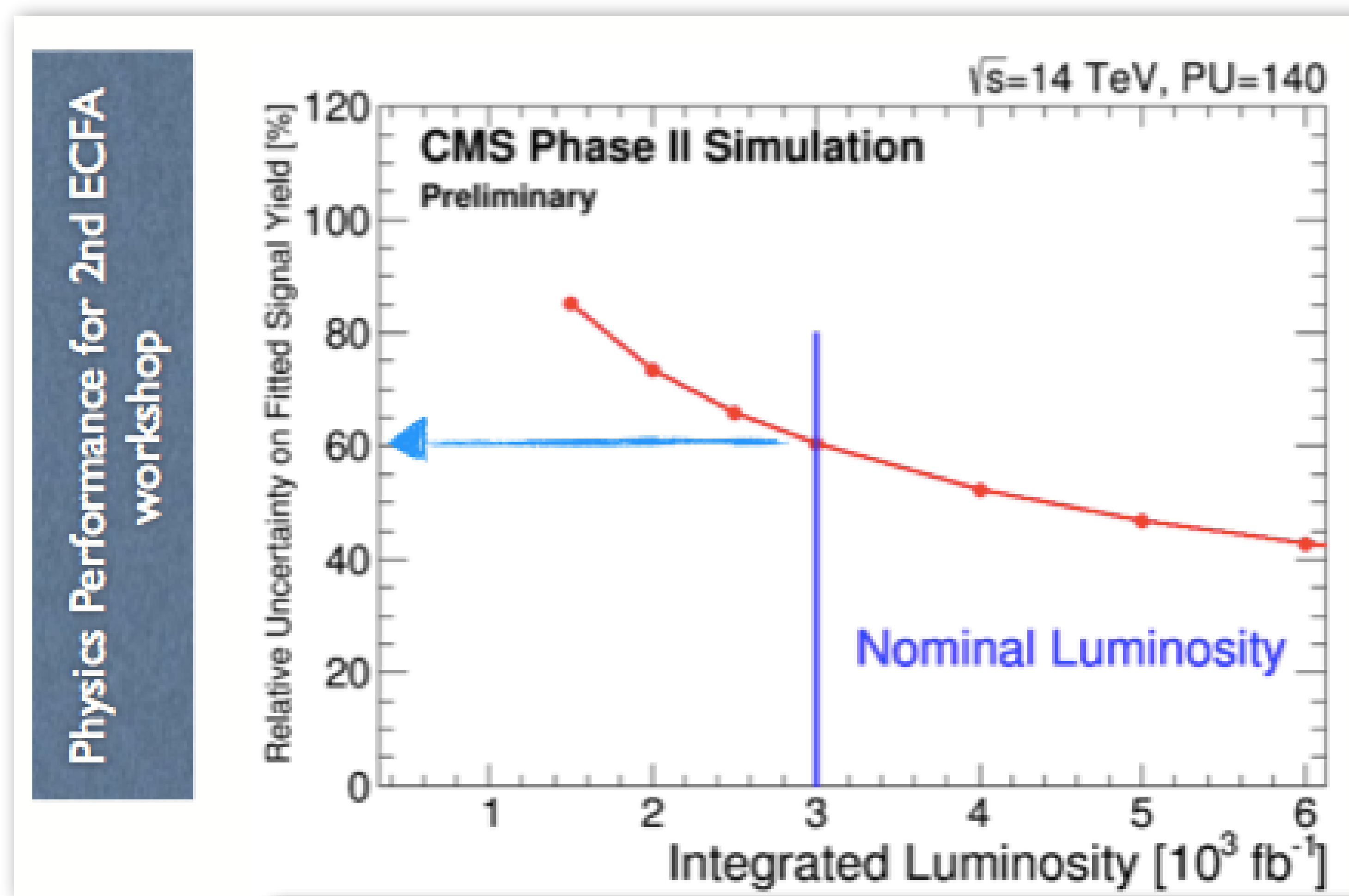
parameters of the potential



$$V(H) \sim m_H^2\,(H-v)^2 \quad + ???$$

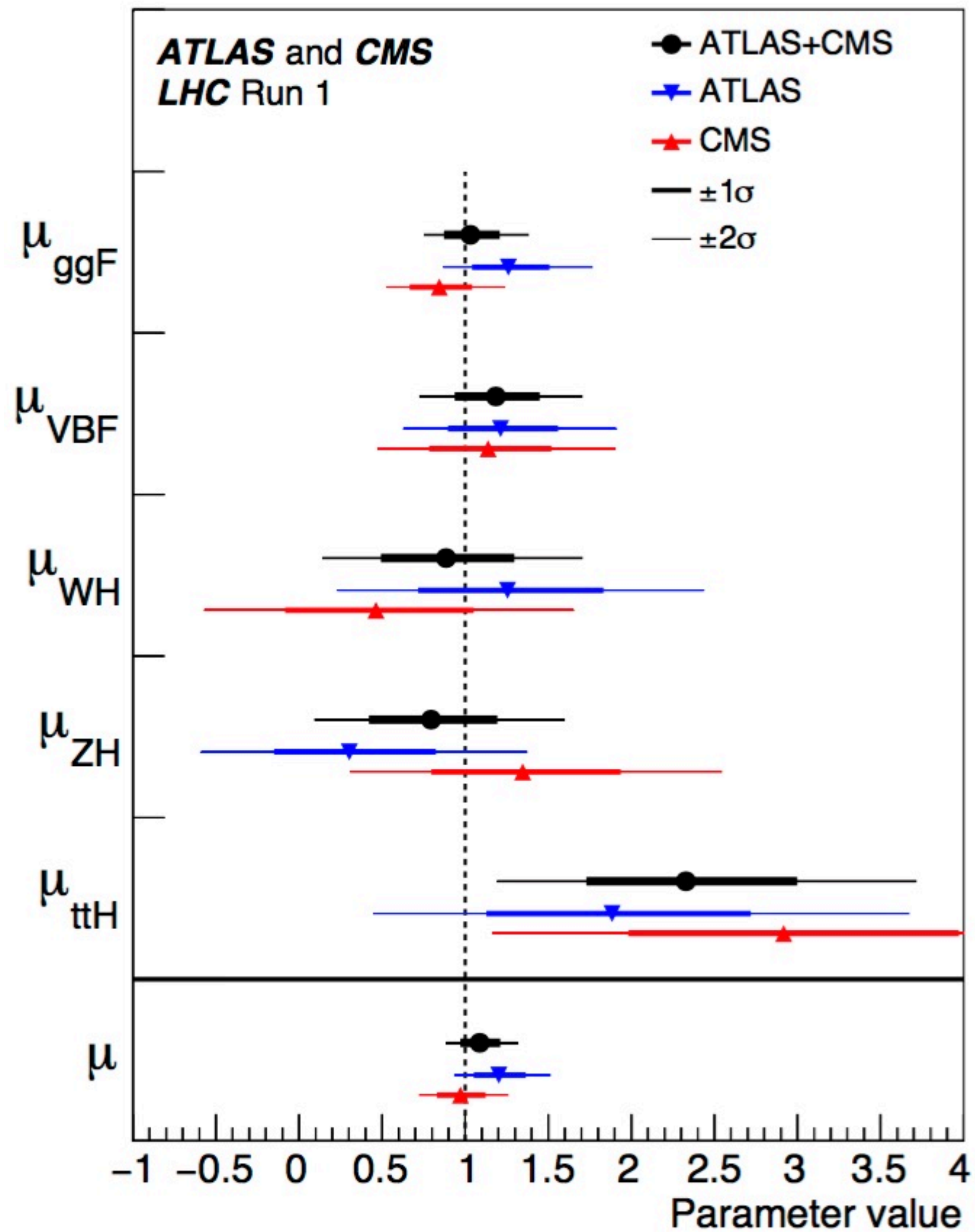
Probing the cubic term of the Higgs potential will require at least 100 x the current LHC statistics, and possibly more





Higgs couplings: global fit of run 1 data

$\mu = \sigma \times BR / [\sigma \times BR]_{SM}$
assuming SM BR's in data



ATLAS+CMS
JHEP 1608 (2016) 045

$\mu = 1.09 \pm 0.11$

- combination of different production and decay channels, explicit constraints on individual couplings are much less precise than 10% !!

- essential to establish couplings individually, through combinations of different production and decay channels

Since run 2:

$H \to \tau\tau$: established at 5.9σ (CMS)

$H \to bb$: established at 3.5σ (ATLAS) and 3.8σ (CMS)

ttH production: established at 4.2σ (ATLAS)

$H \to \mu\mu$: limits at < 2.8 SM (ATLAS) and 2.6 SM (CMS)

Aside from the issue of principle of finding the origin of EWSB, why do we care so much?

The Higgs boson is directly connected to several concrete questions:

- Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^{\pm}$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?
  - does the PT wash out possible pre-existing baryon asymmetry?
- Is there a relation between any amongst Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?

The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

- **New gauge interactions (Z', W') or extra Higgs bosons**
- **Additional fermionic partners of quarks and leptons, leptoquarks, …**
- **Composite nature of quarks and leptons**
- **Supersymmetry, in a variety of twists (minimal, constrained, natural, RPV, …)**
- **Dark matter, long lived particles**
- **Extra dimensions**
- **New flavour phenomena**
- **unanticipated surprises …**

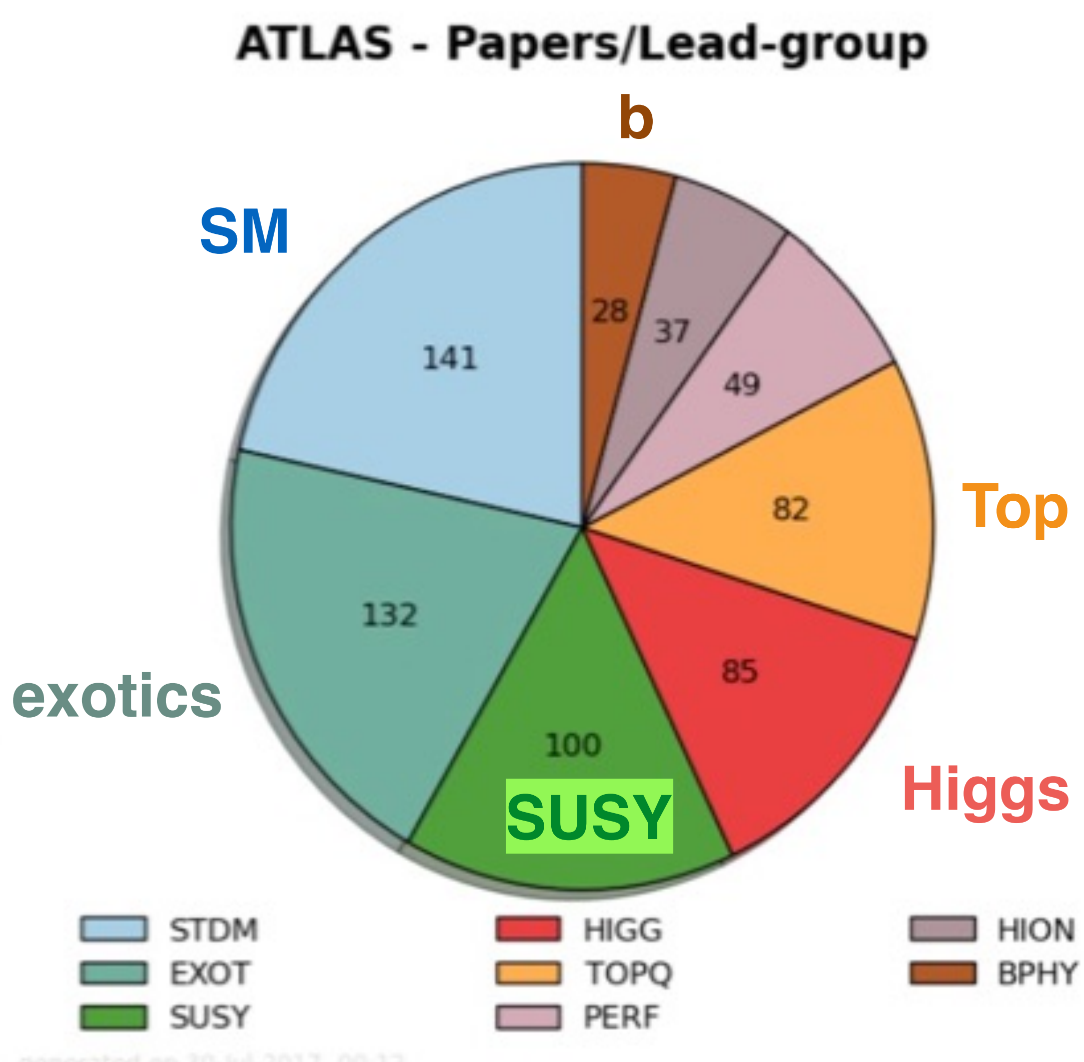
No signal so far, except perhaps from flavour …
=> see Aurelio's and Toni's talks

LHC scientific production (ATLAS, CMS, LHCb)

Papers published/submitted to refereed journals

ATLAS	670
CMS	650
LHCb	396

Programme diversity (ATLAS example, similar stats for the others)



65% of the papers on measurements (ie on "the real world")

35% on searches

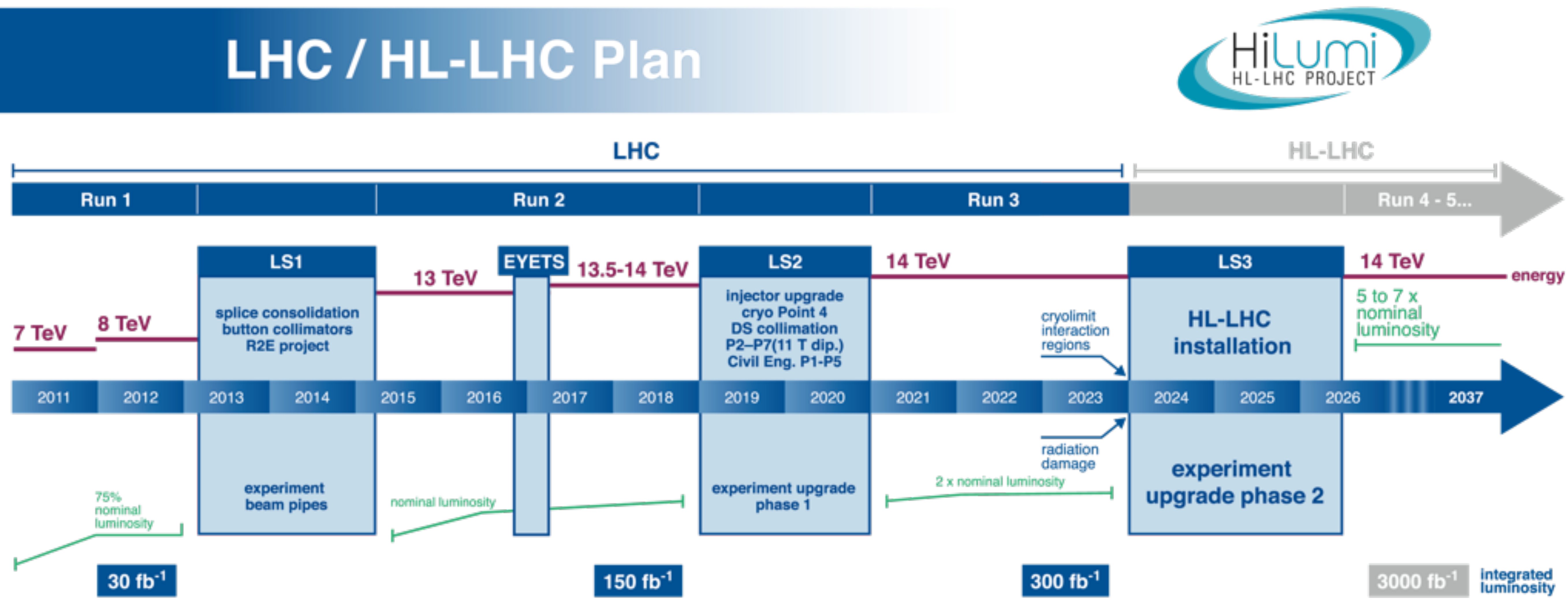
Examples of other research topics covered in these publications

- Extensive programme of searches for BSM
- Rich flavour physics programme
  - precise measurements of CKM from charm/b decays
  - rare processes ($B_{d,s} \to \mu\mu$ decays, …)
- Thorough and extensive studies of QCD dynamics in non-perturbative regimes
  - total, elastic and diffractive cross sections
  - PDF determinations via precise XS measurements (W/Z, jets, hvq's)
  - exotic hadrons: tetra- and pentaquark spectroscopy, glueball searches via exclusive diffractive pp reactions, …
  - hadron production in the fwd region (implications for modeling of cosmic-ray showers in the atmosphere)
  - collective phenomena in pp, pA and AA collisions (the "ridge" effect)
  - nuclear PDF determinations with the pA programme
  - heavy ion collisions, QGP

Remarks

- These 1700 papers reflect the underlying existence, at the LHC, of 100's of scientifically "independent" experiments, which historically would have required different detectors and facilities, built and operated by different communities
- On each of these topics the LHC expts are advancing the knowledge previously acquired by dedicated facilities
  - HERA→PDFs, B-factories→flavour, RHIC→HIs, LEP/SLC→EWPT, etc
- Even in the perspective of new dedicated facilities, LHC maintains a key role of complementarity (see eg $B_{(s)} \to \mu\mu$ etc)

Long-term LHC plan



The ~100fb^{-1} so far are just 3% of the final statistics

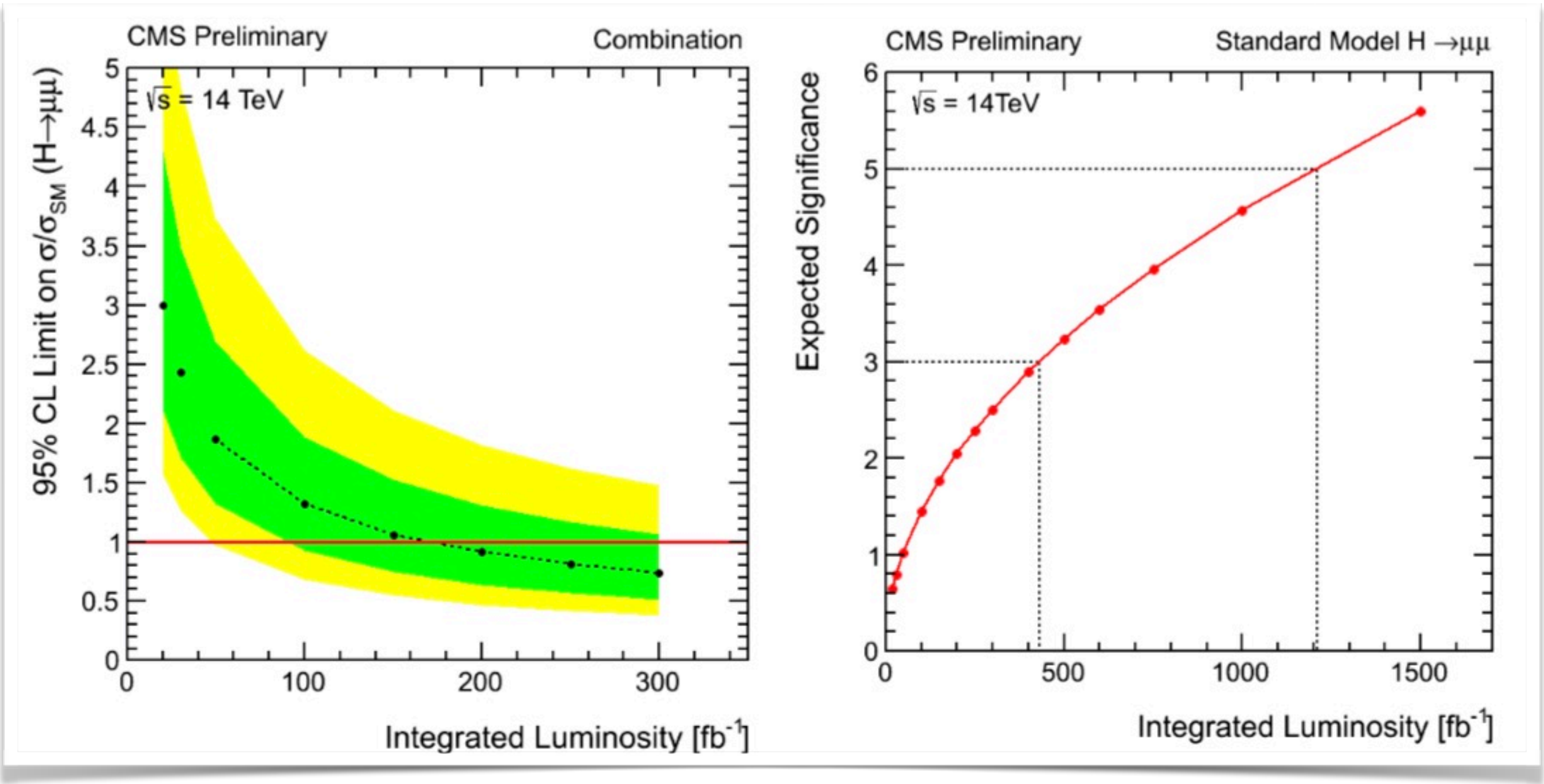
==>> the LHC physics programme has barely started! <<==

Future evolution of Higgs statistics

	$\mathcal{L}$ [fb^{-1}]	All	$H \to \gamma\gamma$	$H \to ZZ \to 4l$	$H \to WW^* \to l\nu l\nu$
July '16	13.3	0.75M	600	20	400
End '18	120	7M	6,000	200	4,000
End '23	300	17M	14,000	500	10,000
~ 2035	3000	170M	140,000	5,000	100,000

include estimates of analysis cuts and efficiencies

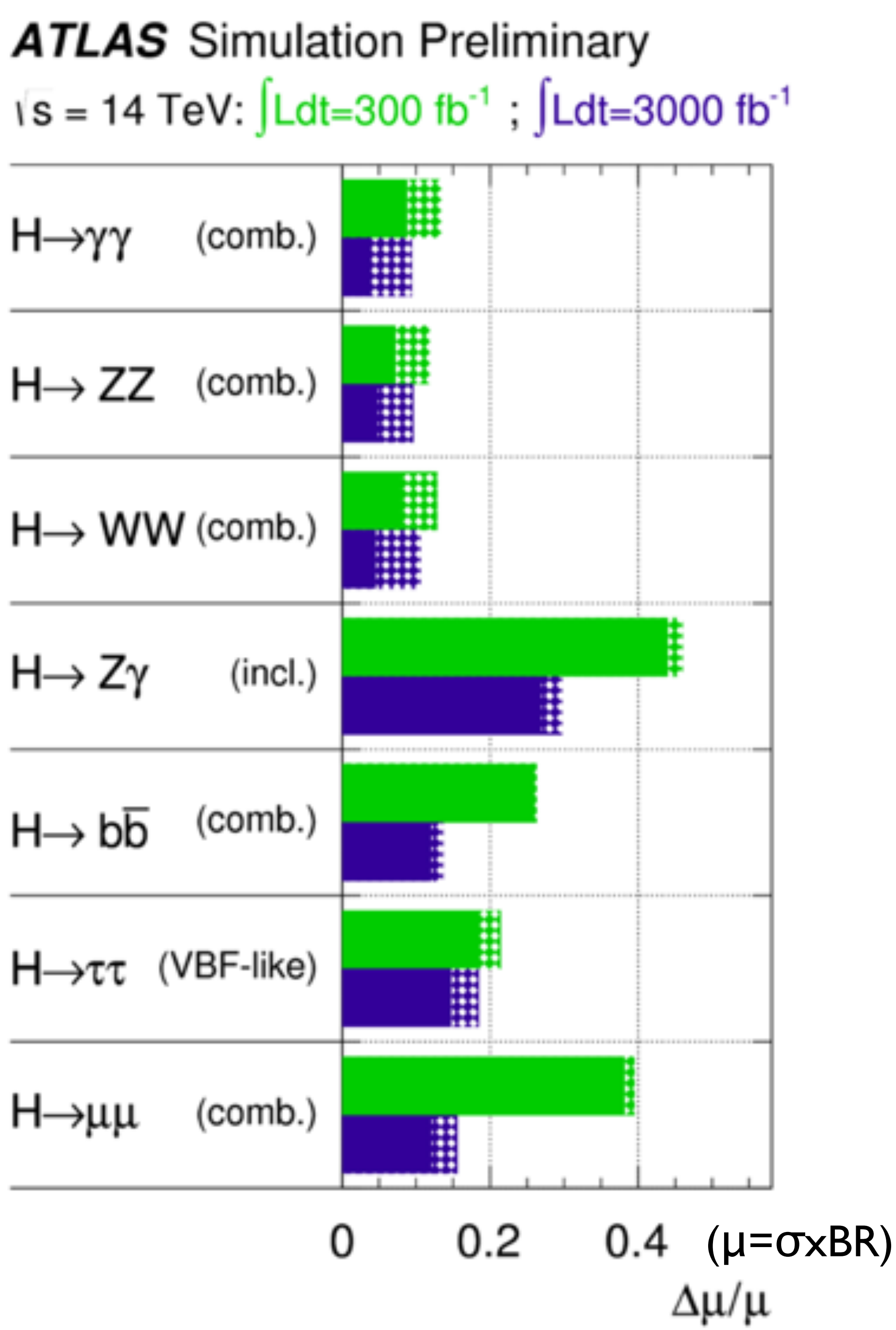
Projections for H couplings to 2nd generation

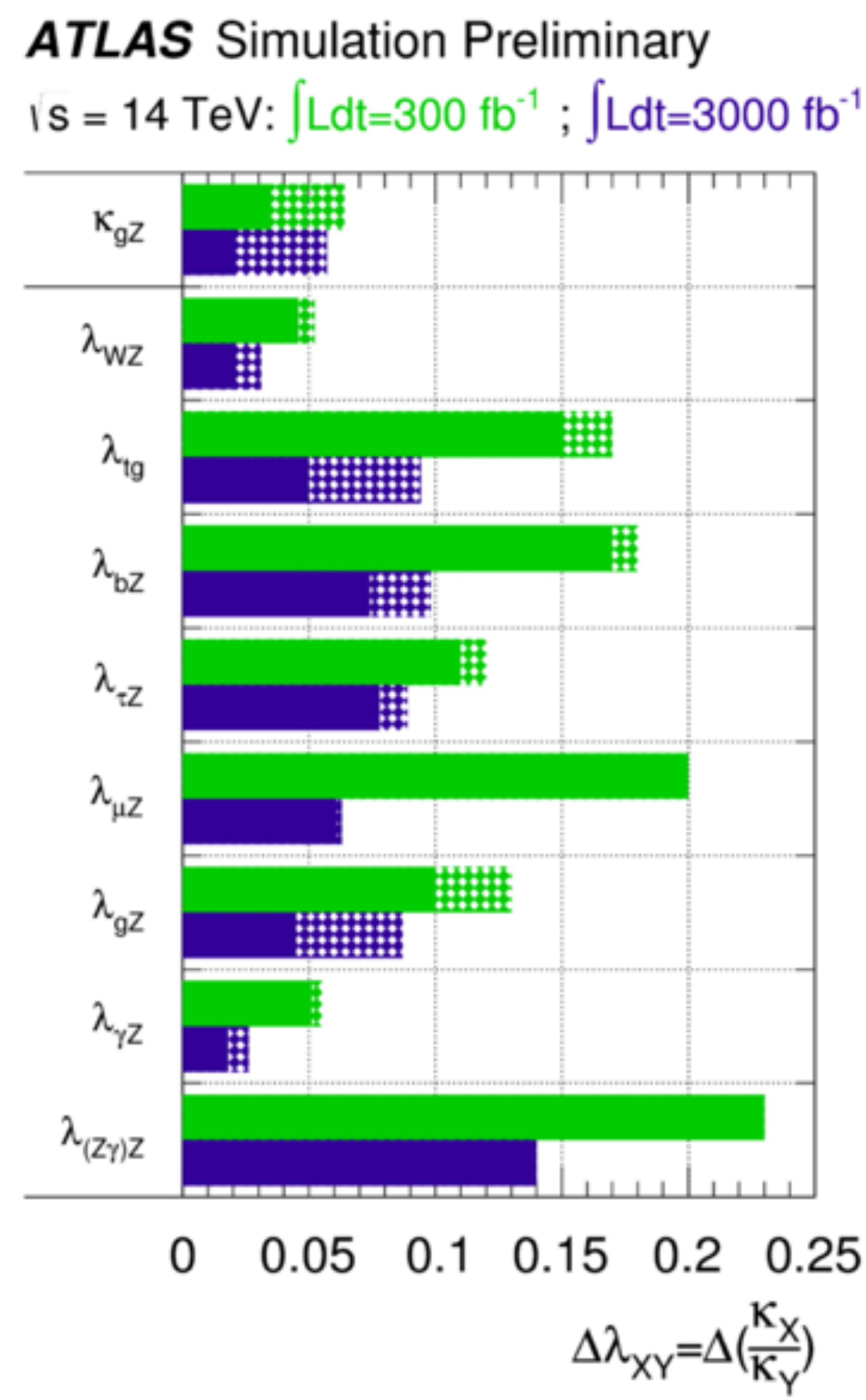


Projections from CMS-HIG-13-007

Projected precision on H couplings

ATL-PHYS-PUB-2014-016





solid areas: no TH systematics

shaded areas: with TH systematics

- **SUSY (tanβ=5):** $$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

- **Composite Higgs:** $$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

- **Top partners:** $$\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \qquad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$$

HL-LHC full statistics needed to approach these sensitivities, but barely enough!

Beyond the LHC

Remark

the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field

Key question for the future developments of HEP: Why don’t we see the new physics we expected to be present around the TeV scale ?

- **Is the mass scale beyond the LHC reach ?**

- **Is the mass scale within LHC’s reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:
- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

The physics potential (the "case") of a future facility for HEP should be weighed against criteria such as:

(1) the **guaranteed deliverables:**

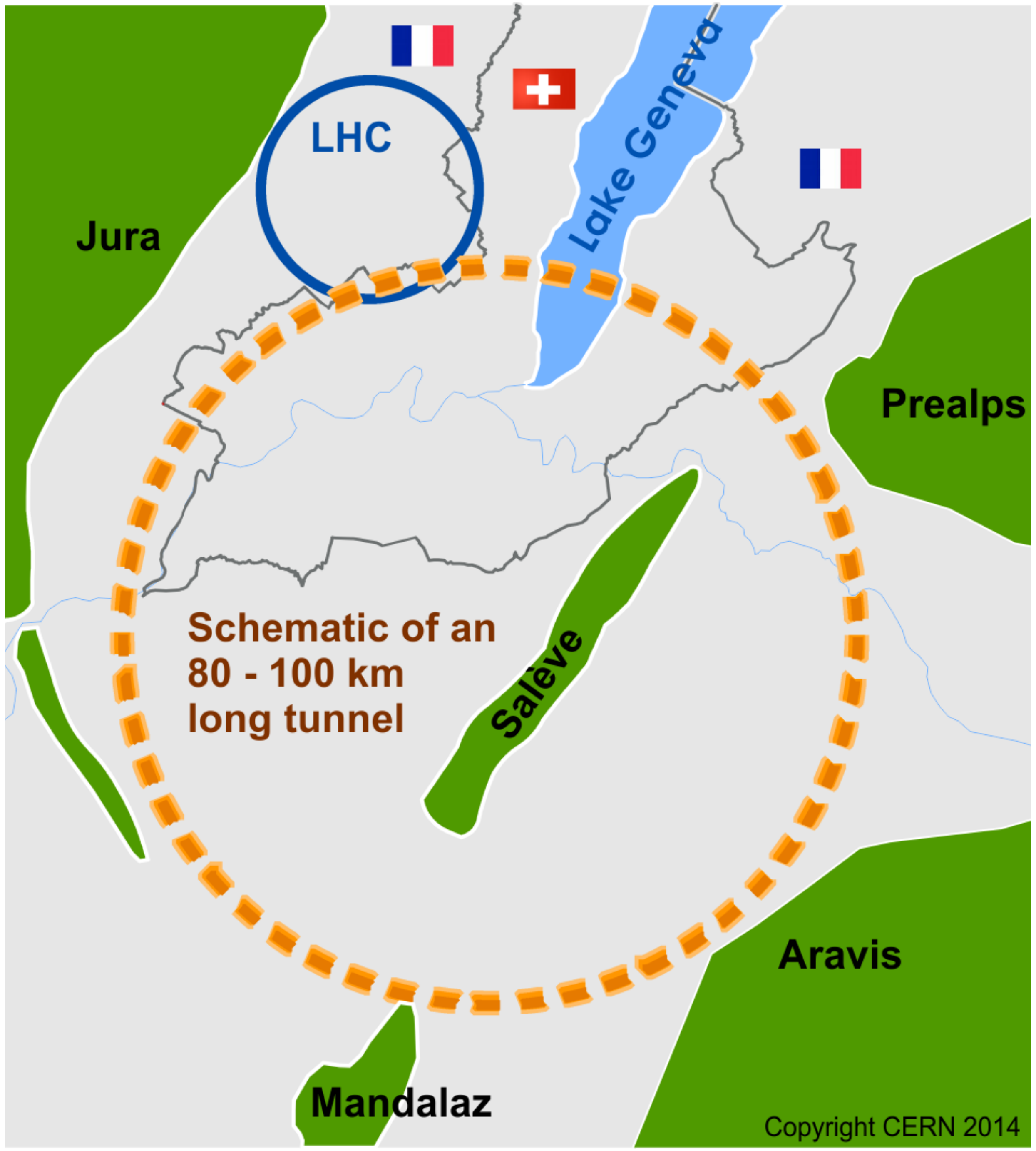
- knowledge that will be acquired independently of possible discoveries (*the value of "measurements"*)

(2) the **exploration potential:**

- target broad and well justified BSM scenarios .... *but guarantee sensitivity to more exotic options*
- exploit both direct (large Q^2) and indirect (precision) probes

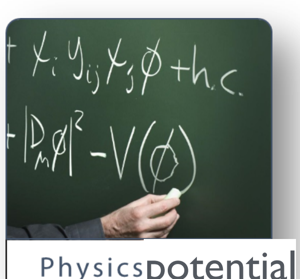
(3) the potential to provide conclusive **yes/no answers** to relevant, broad questions.

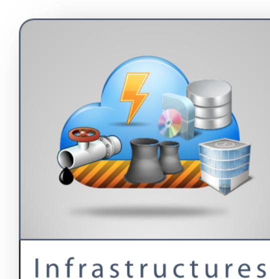
Future Circular Colliders (FCC)

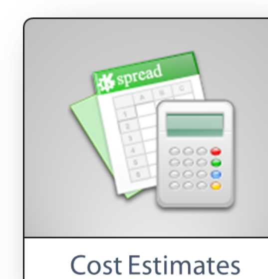


International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements
  ~16 T ⇒ 100 TeV *pp* in 100 km
- **~100 km tunnel infrastructure**
  in Geneva area, site specific
- ***e⁺e⁻* collider (*FCC-ee*),**
  as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,**
  integration of one IP, e from ERL
- **CDR for end 2018**







CEPC & SPPC

http://cepc.ihep.ac.cn

The potential of a Future Circular Collider

- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with unmatchable **precision and sensitivity**
- Exploration potential:
  - **mass reach enhanced** by factor ~ E / 14 TeV (will be 5–7 at 100 TeV, depending on integrated luminosity)
    - *statistics enhanced by several orders of magnitude for BSM phenomena brought to light by the LHC*
  - benefit from both direct (large Q^2) and indirect (precision) probes
- Provide firm Yes/No answers to questions like:
  - is the SM dynamics all there is at the TeV scale?
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - did baryogenesis take place during the EW phase transition?

The basic motivation for Future Circular Colliders (FCC)

- HEP has two priorities:
  - **explore the physics of electroweak symmetry breaking**:
    - experimentally, via the measurement of Higgs properties, Higgs interactions and selfinteractions, couplings of gauge bosons, flavour phenomena, etc
    - theoretically, to understand the nature of the hierarchy problem and identify possible natural solutions (to be subjected to exptl test)
  - **explore the origin of known departures from the SM** (DM, neutrino masses, baryon asymmetry of the universe)

The physics case of FCCs builds on the belief that these two directions are deeply intertwined

Examples: precision Higgs physics

Higgs couplings @ FCC-ee

g_{HXY}	ee [240+350 (4IP)]
ZZ	**0.15%**
WW	**0.19%**
bb	**0.42%**
cc	**0.71%**
gg	**0.80%**
ττ	**0.54%**
μμ	**6.2%**
γγ	**1.5%**
Zγ	
tt	**~13%**
HH	**~30%**
uu,dd	H->ργ, under study
ss	H->φγ, under study
BR_{inv}	**< 0.45%**
Γ_{tot}	**1%**

SM Higgs at 100 TeV

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$

$N_8 = \sigma_{8\,\mathrm{TeV}} \times 20\ \mathrm{fb}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

- Huge production rates imply:
  - can afford reducing statistics, with tighter kinematical cuts that reduce backgrounds and systematics
  - can explore new dynamical regimes, where new tests of the SM and EWSB can be done

Remarks

- Higher statistics shifts the balance between systematic and statistical uncertainties. It can be exploited to define different signal regions, with better S/B, better systematics, pushing the potential for better measurements beyond the "systematics wall" of low-stat measurements.
- We often talk about "**precise**" Higgs measurements. What we actually aim at is "**sensitive**" tests of the Higgs properties, where *sensitive* refers to the ability to reveal BSM behaviours.
- *Sensitivity* may not require extreme precision
  - Going after "sensitivity", rather than *just* precision, opens itself new opportunities …

Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = |\, \langle f|L|i\rangle \,|^2 = O_{SM} \left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

e.g. δO=1% ⇒ Λ ~ 2.5 TeV

For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

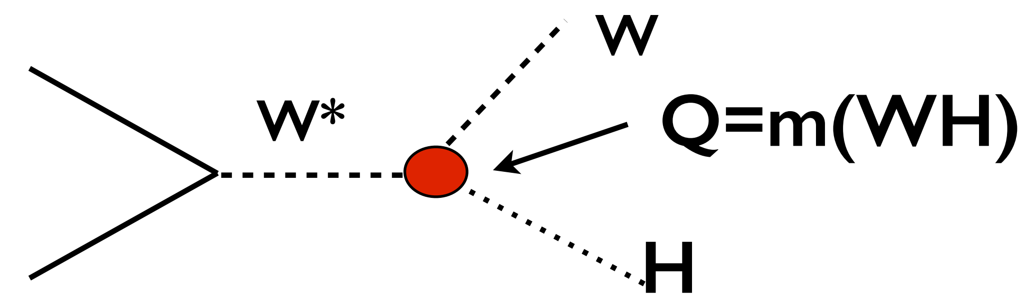
$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

⇒ **kinematic reach** probes large Λ even if precision is low

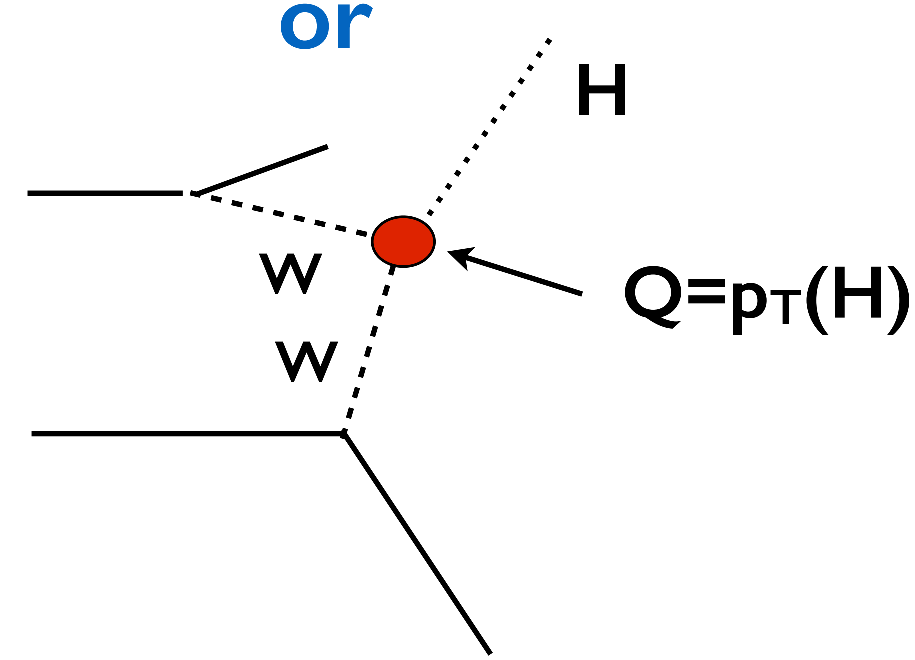
e.g. δO=15% at Q=1 TeV ⇒ Λ~2.5 TeV

Examples

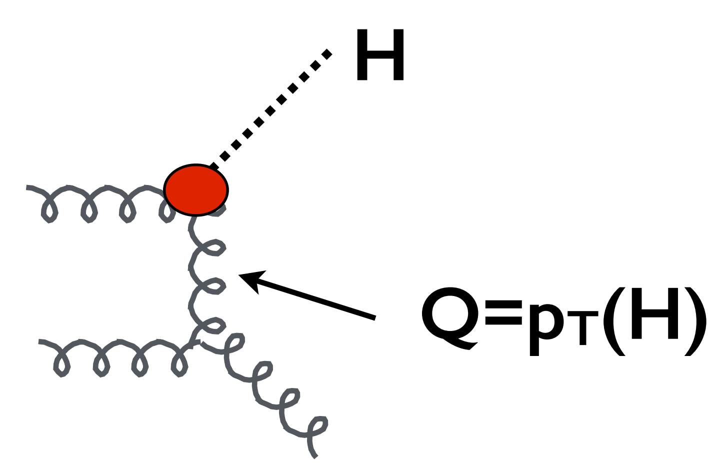
δBR(H→WW*)



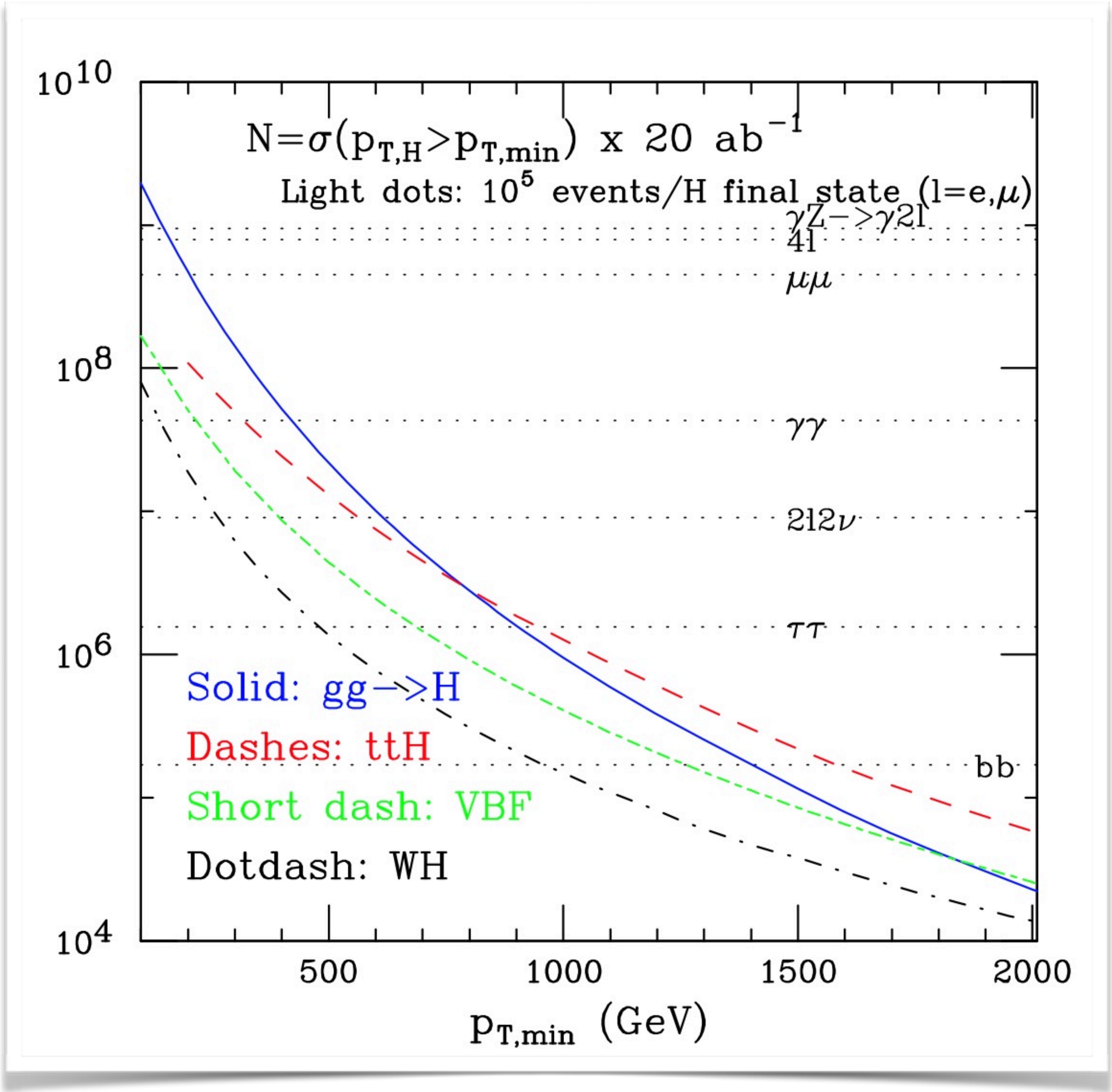
or



δBR(H→gg)

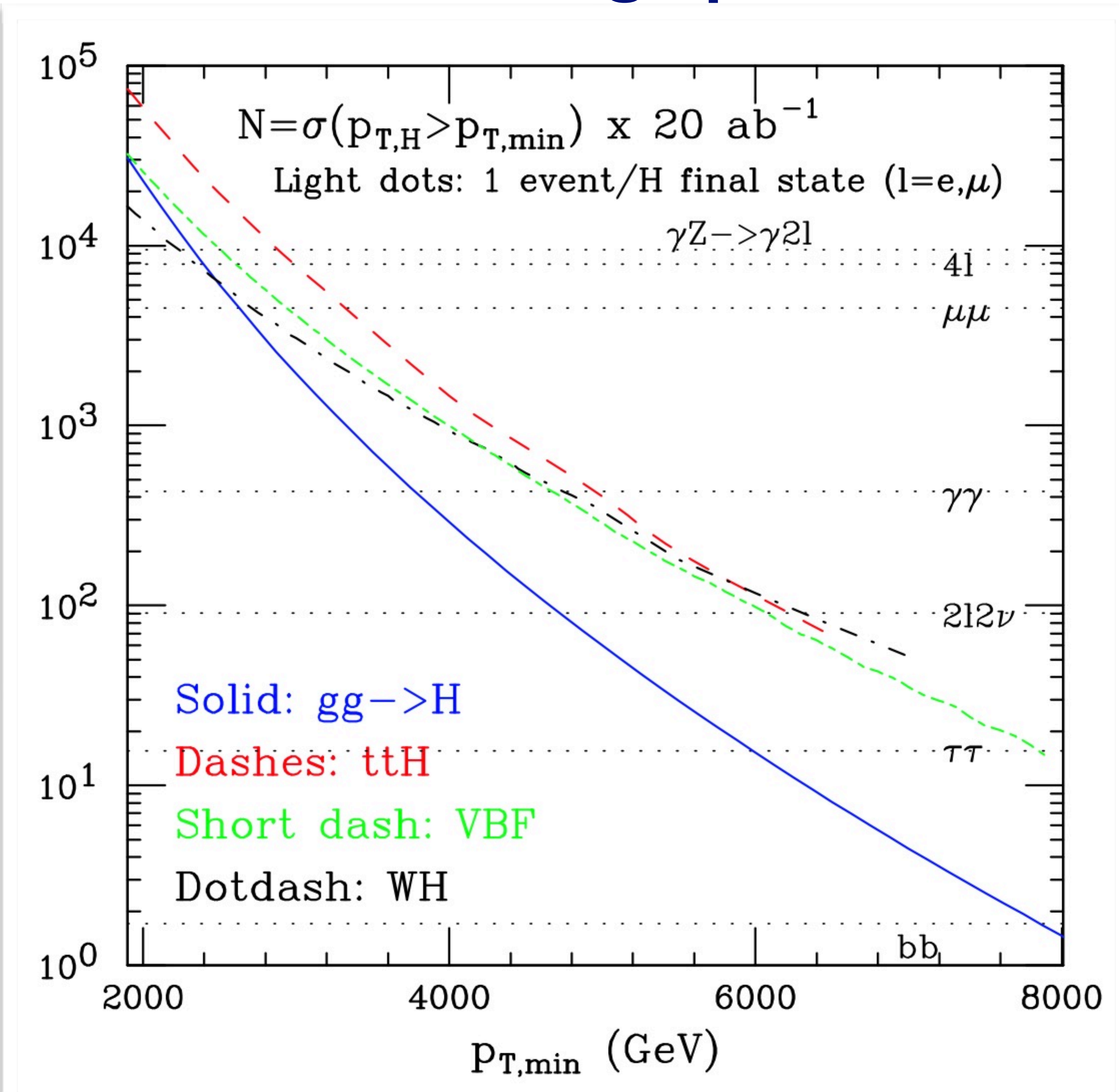


H at large p_T



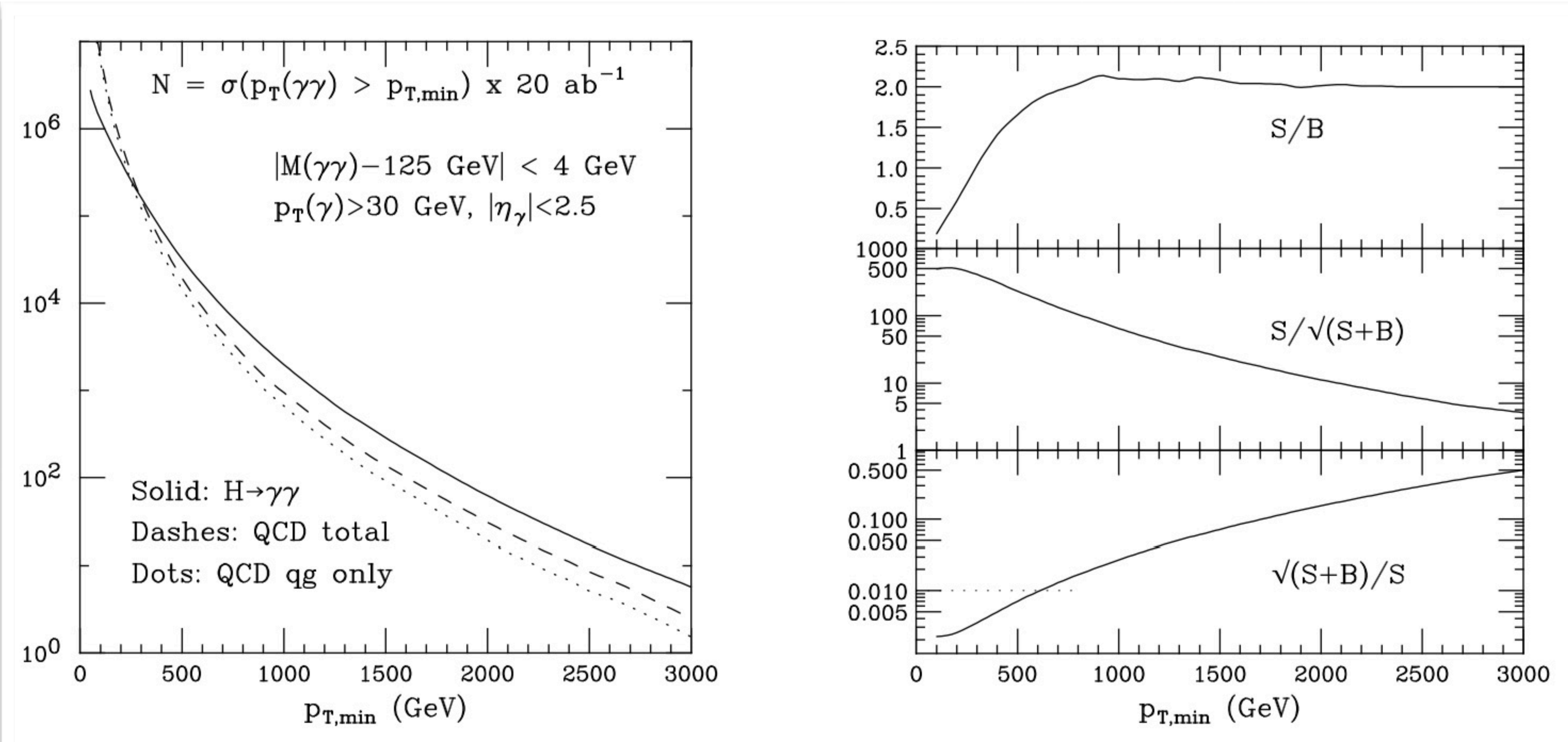
- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg \to H)$ above 1800 GeV

H at large p_T



- Statistics in potentially visible final states out to several TeV

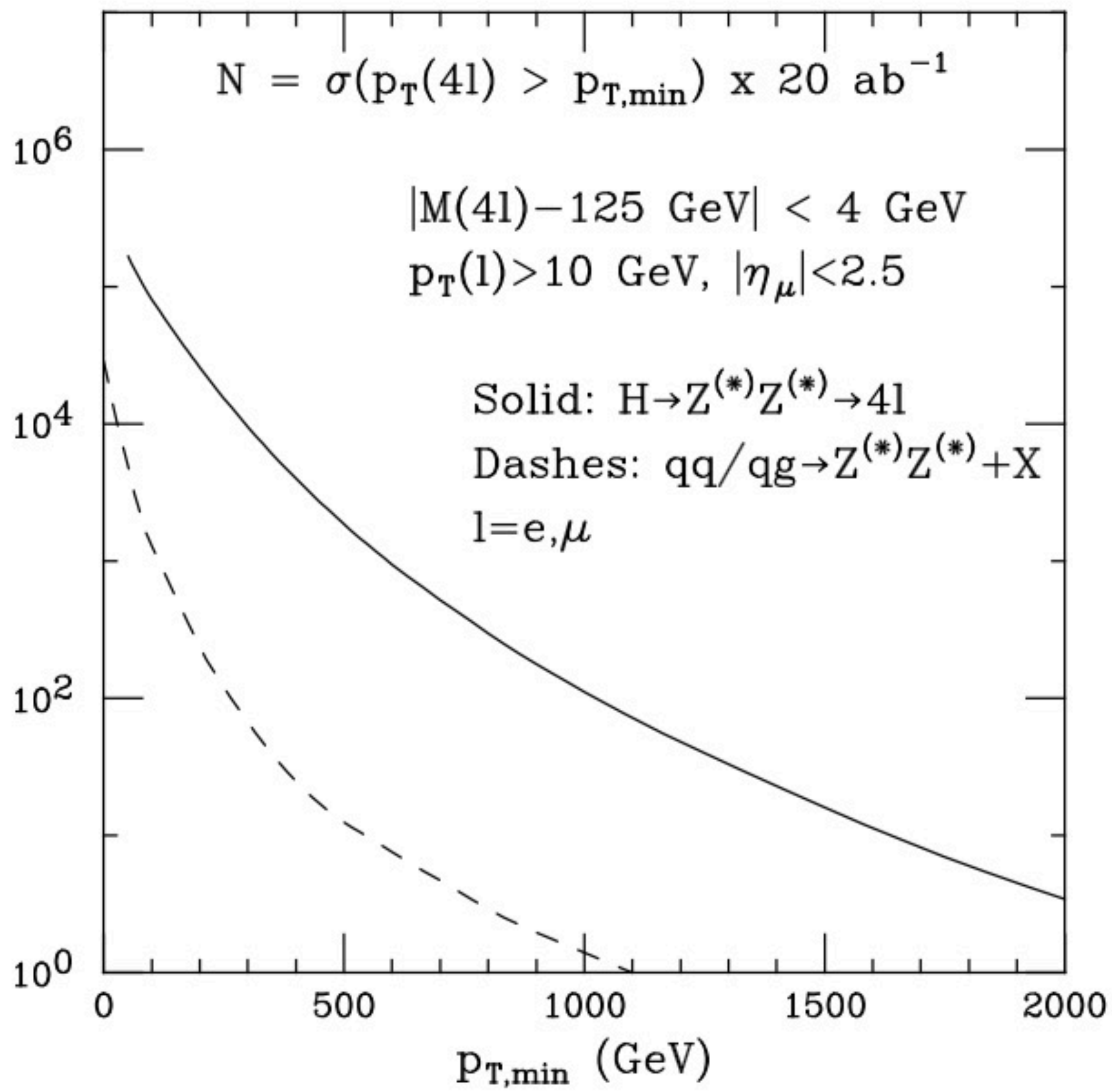
$gg \to H \to \gamma\gamma$ at large p_T

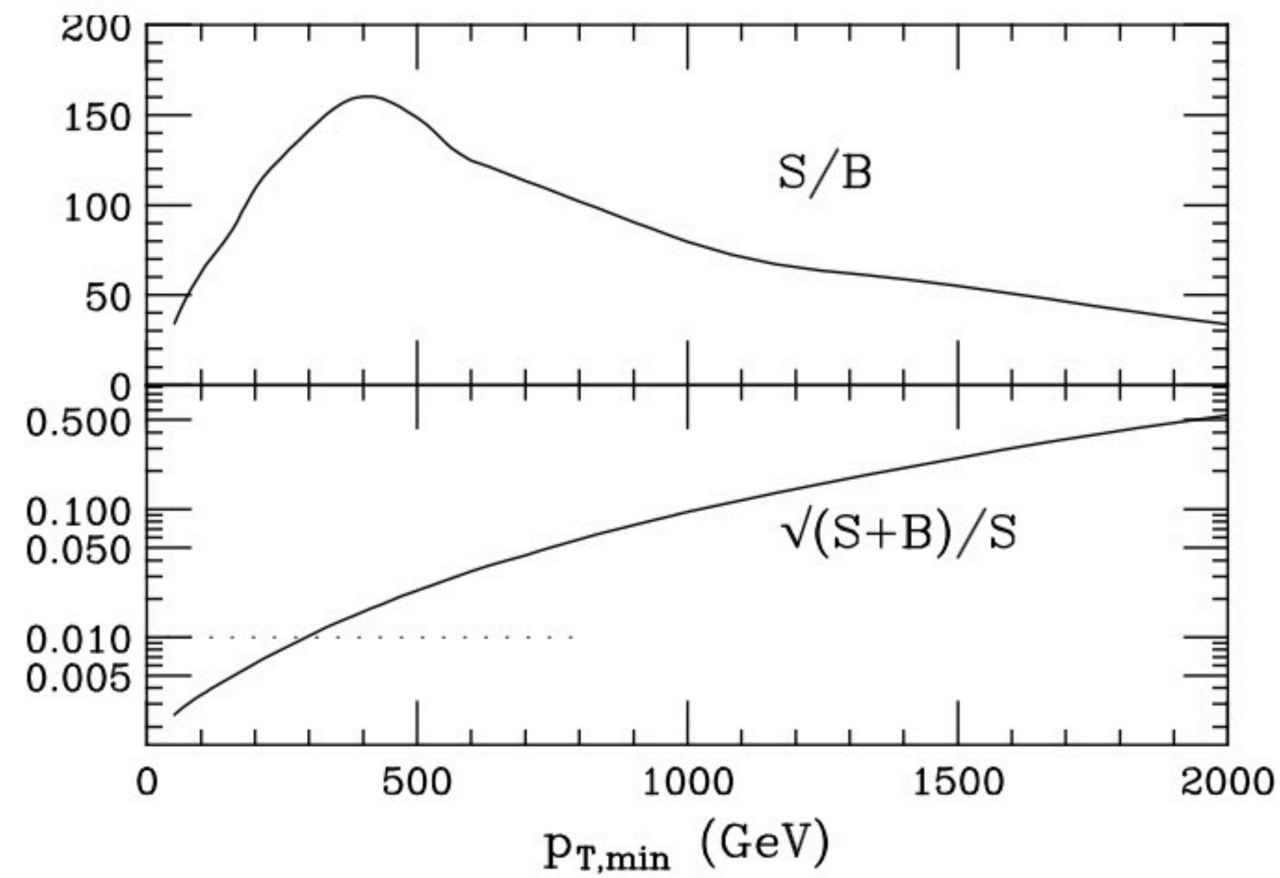


- At LHC, S/B in the $H \to \gamma\gamma$ channel is O(few %)
- At FCC, for $p_T(H)>300$ GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%

gg→H→ZZ*→4l at large p_T

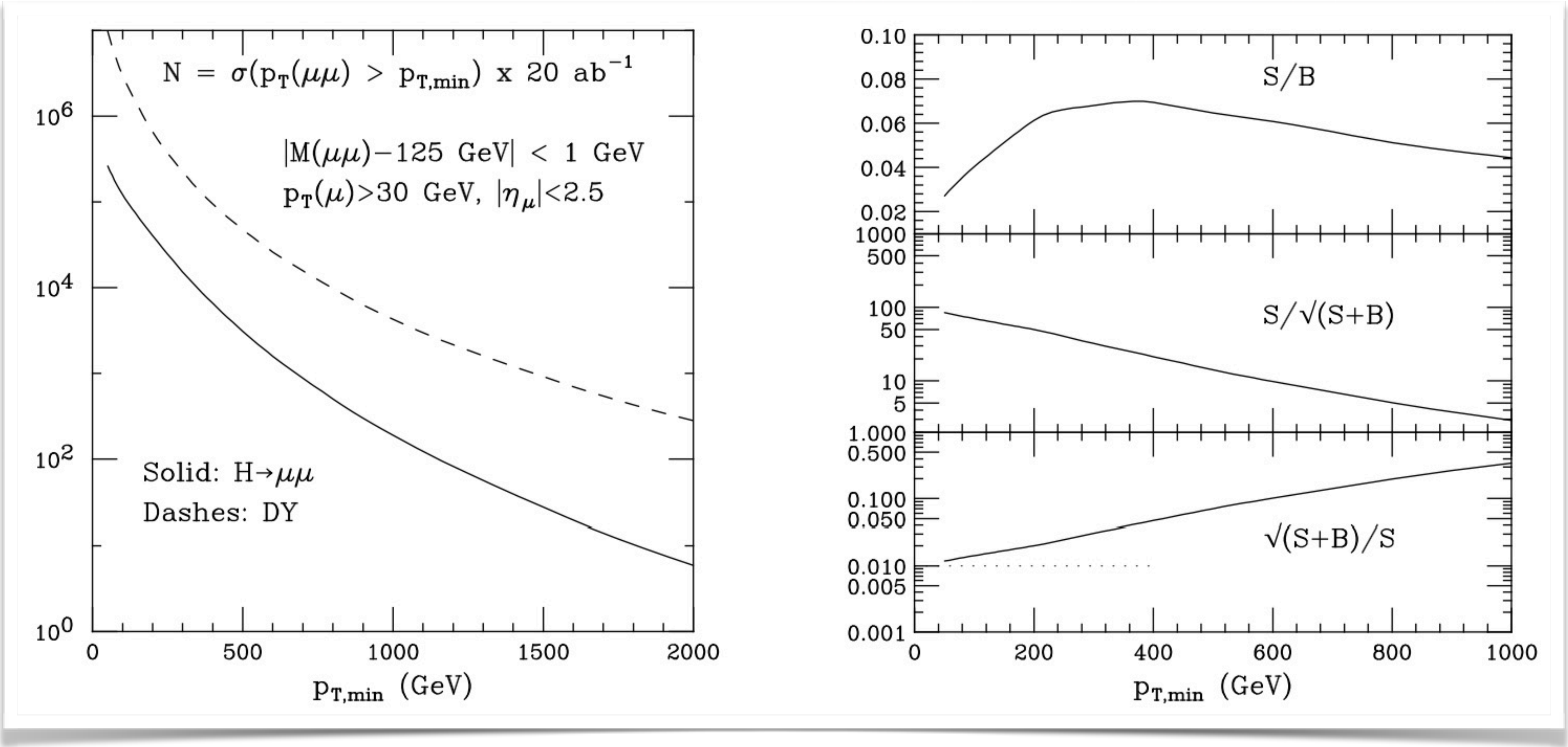




- S/B ~ 1 for inclusive production at LHC
- Practically bg-free at large p_T at 100 TeV, maintaining large rates

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.3%**
300	**1%**
1000	10%

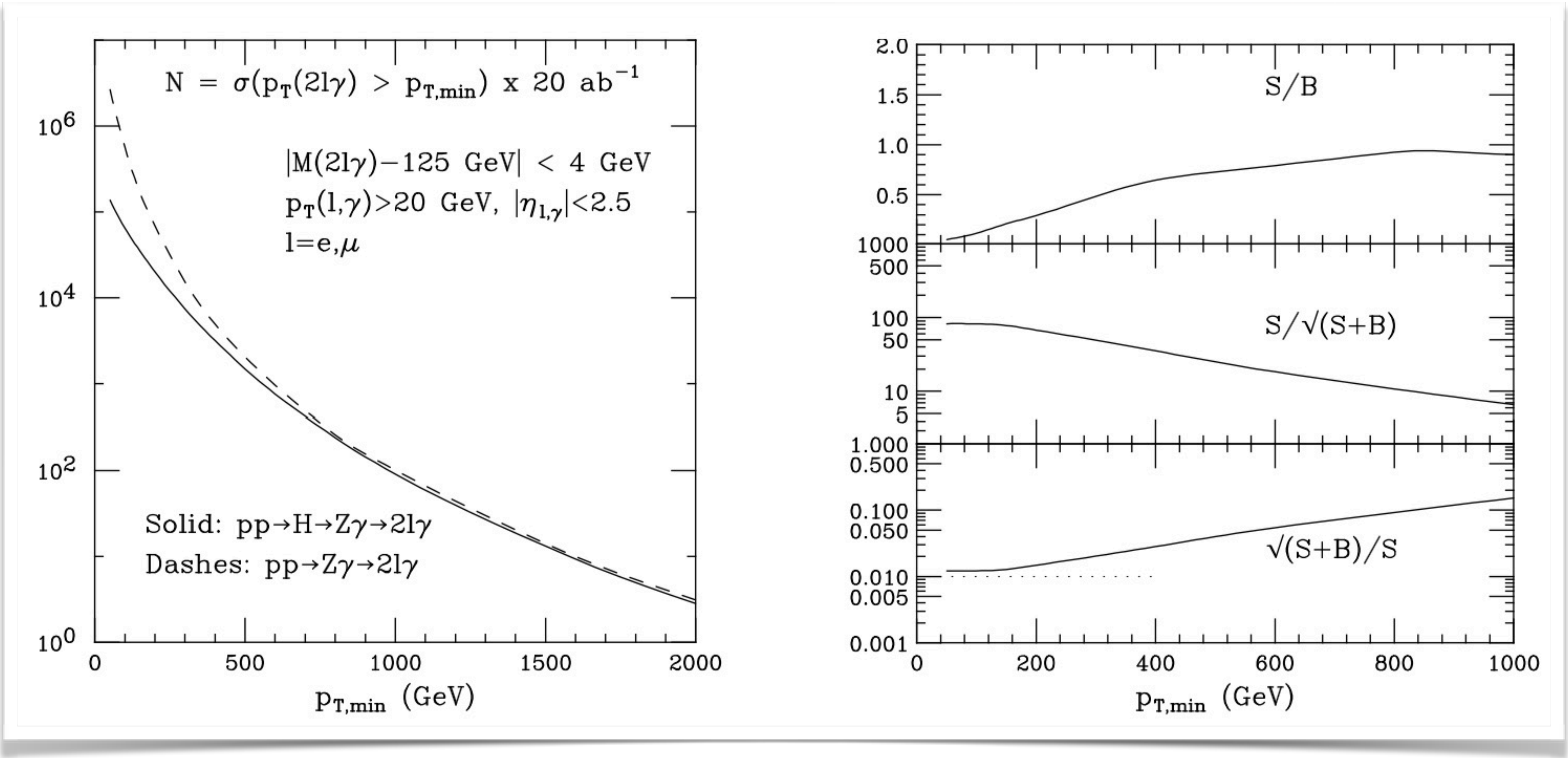
$gg \to H \to \mu\mu$ at large p_T



- Stat reach ~1% at p_T~100 GeV
- Exptl systematics on BR(μμ)/BR(γγ)? (use same fiducial selection to remove H modeling syst's)

$p_{T,min}$ (GeV)	δ_{stat}
100	**1%**
500	10%

$gg \to H \to Z\gamma \to \ell\ell\gamma$ at large p_T

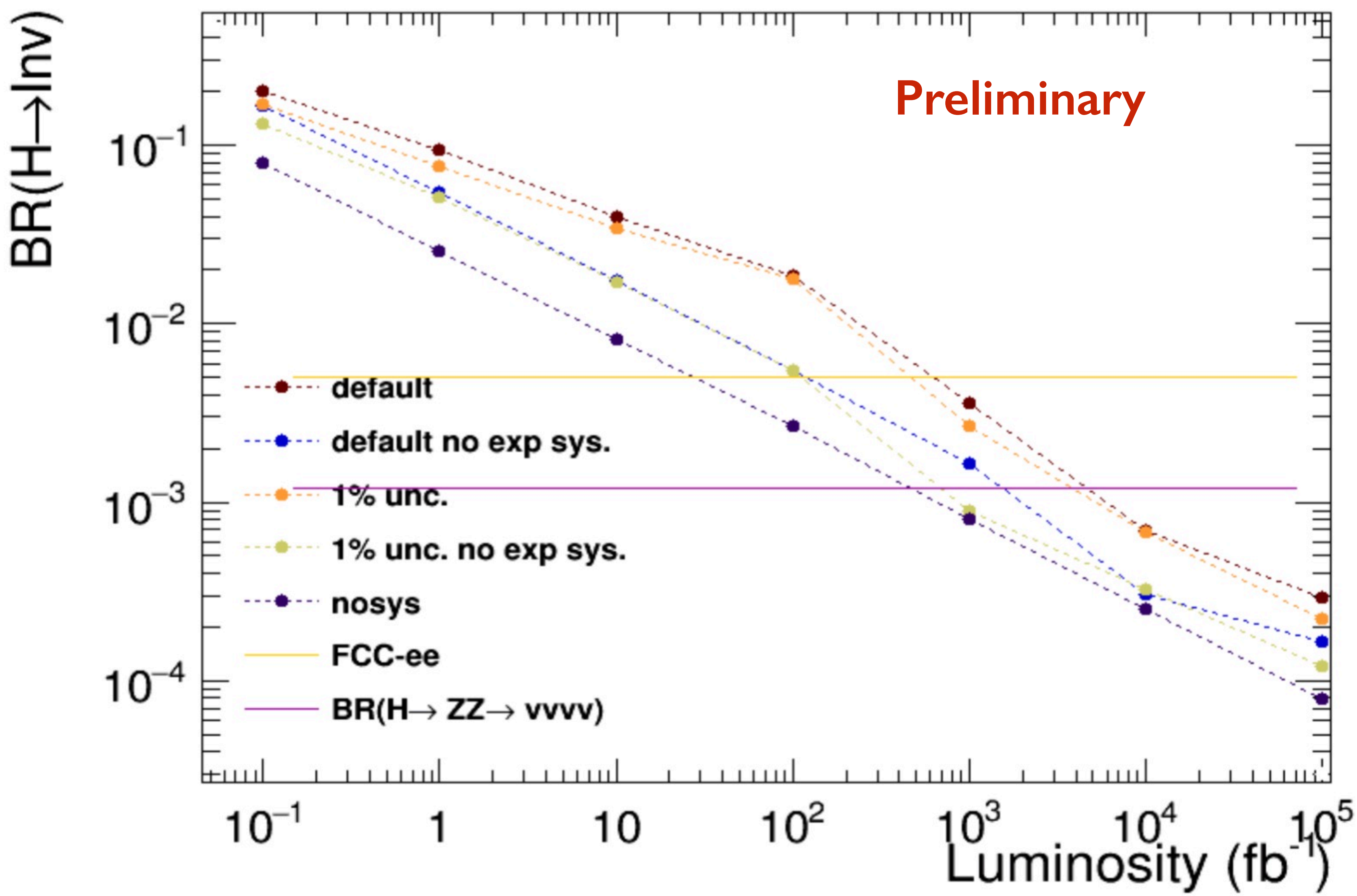


- S/B → 1 at large p_T
- Stat reach ~1% at pT~100 GeV
- Exptl systematics on BR(Zγ)/BR(γγ)?

$p_{T,min}$ (GeV)	δ_{stat}
100	**1%**
900	10%

BR(H→inv) in H+X production at large p_T(H)

Constrain bg pt spectrum from Z→νν to the % level using NNLO QCD/EW to relate to measured Z→ee, W and γ spectra



SM sensitivity with 1ab^{-1}, can reach few x 10^{-4} with 30ab^{-1}

Higgs couplings @ FCC

g_{HXY}	ee [240+350 (4IP)]	pp [100 TeV] 30ab^{-1}	ep [60GeV/50TeV], 1ab^{-1}
ZZ	0.15%	under study	
WW	0.19%		
bb	0.42%		0.2%
cc	0.71%		1.8%
gg	0.80%		
ττ	0.54%		
μμ	6.2%	<1%	
γγ	1.5%	<0.5%	
Zγ		<1%	
tt	~13%	1%	
HH	~30%	3.5%	under study
uu,dd	H->ργ, under study		
ss	H->φγ, under study		
BR_{inv}	< 0.45%	< 0.1%	
Γ_{tot}	1%		

- detailed study, stat+syst
- rather detailed, stat only (understood/limited/negligible theory syst)
- parton level S and B (from ratios, negligibleTH syst, small exp syst)
- very preliminary estimates of exp/th syst (not stat-limited)

One should not underestimate the value of FCC-hh standalone precise "ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

BR(H→γγ)/BR(H→ZZ*)

loop-level tree-level

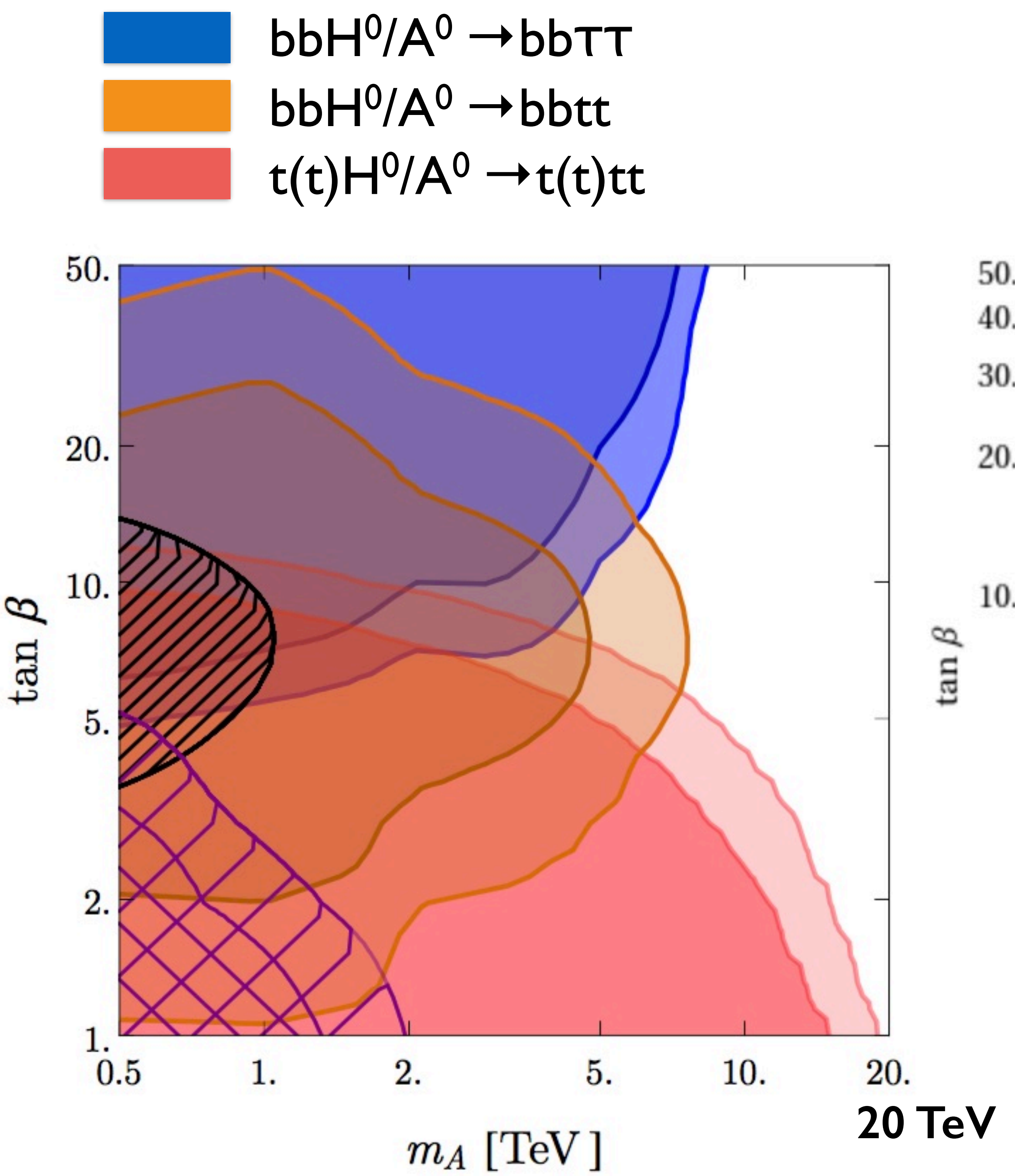
BR(H→μμ)/BR(H→ZZ*)

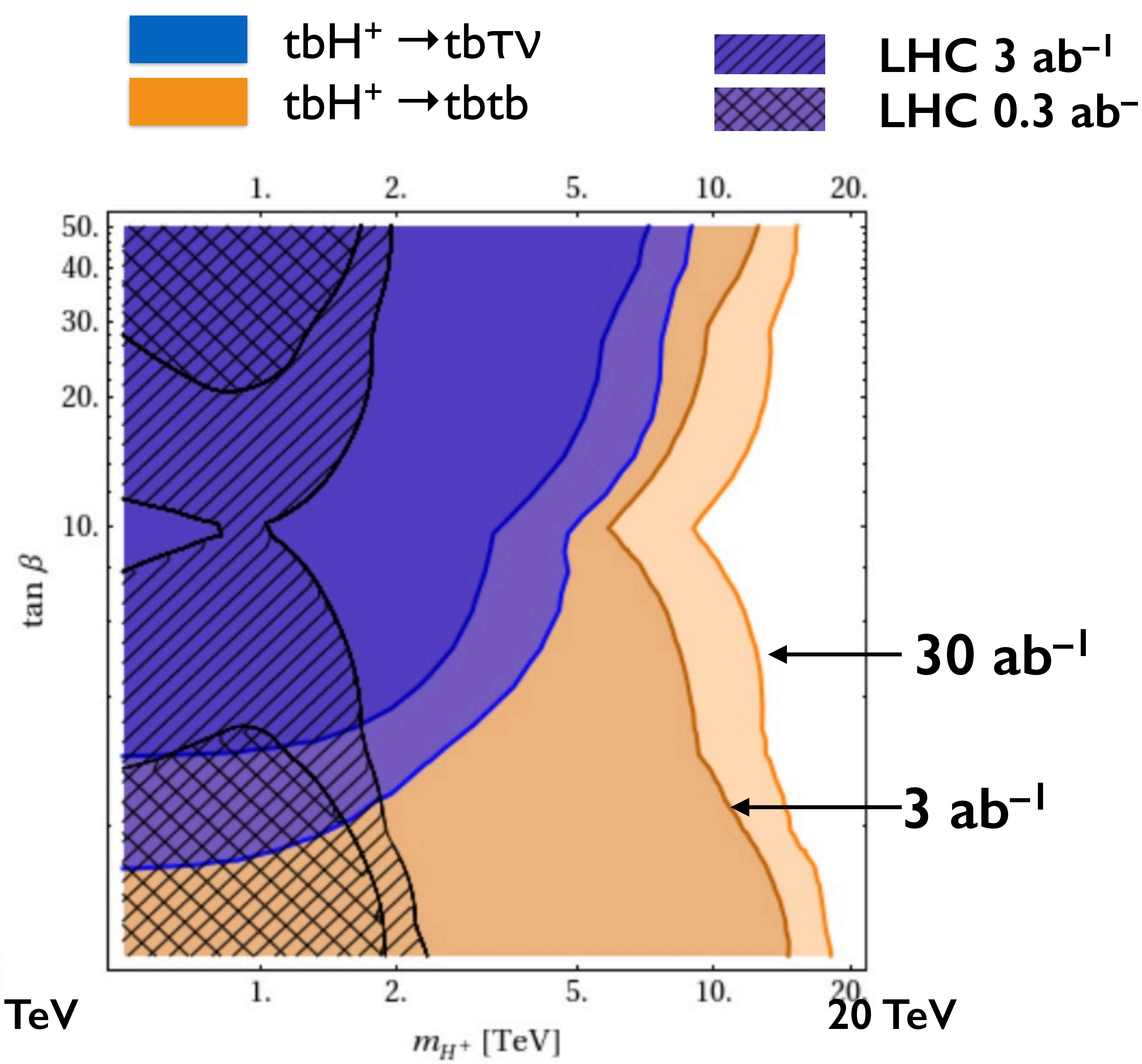
2nd gen'n Yukawa gauge coupling

BR(H→γγ)/BR(H→Zγ)

different EW charges in the loops of the two procs

MSSM Higgs @ 100 TeV





N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang, arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617

Minimal stealthy model for a strong EW phase transition:
the most challenging scenario for discovery

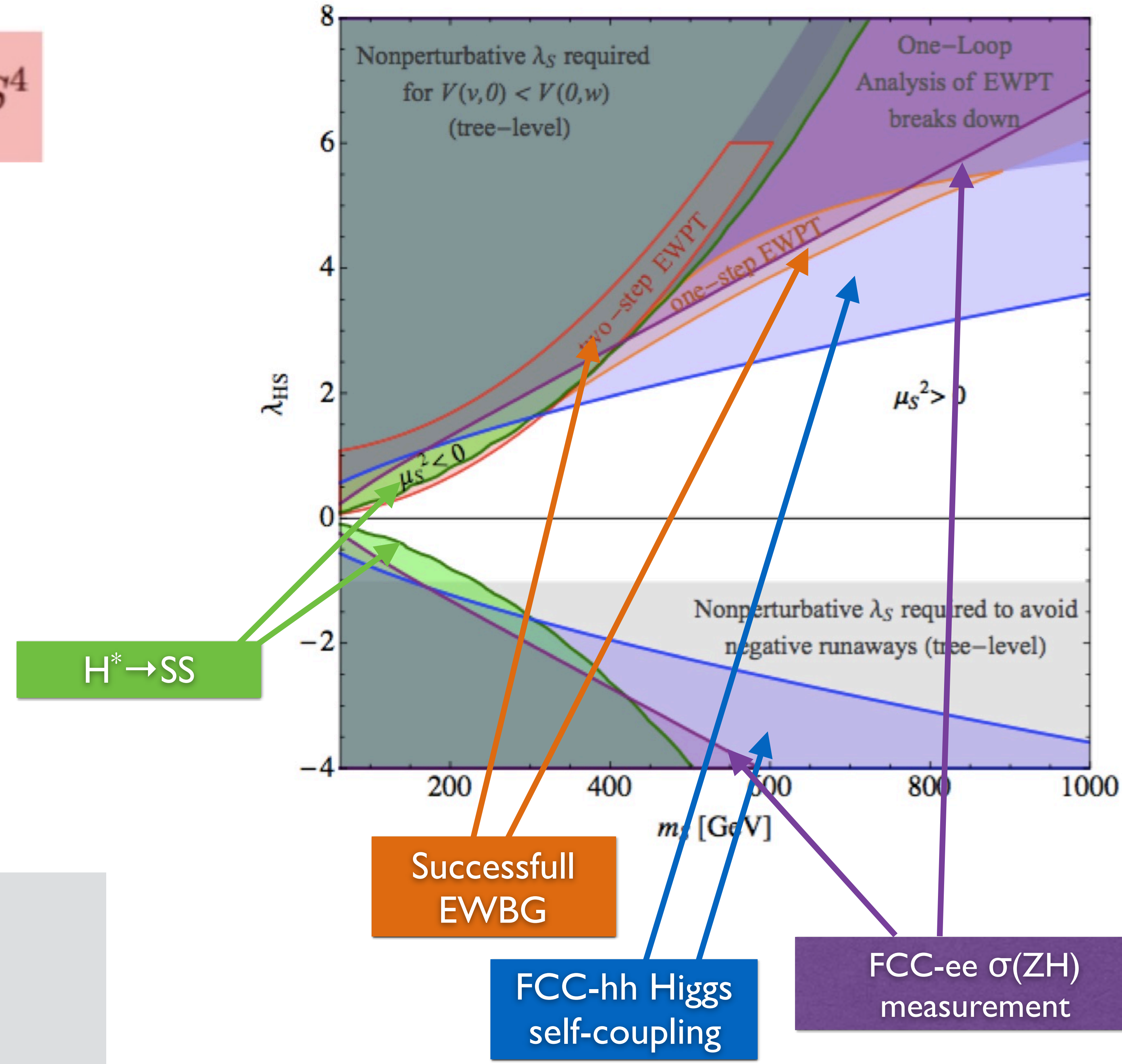
$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \boxed{\frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4}$$

Unmixed SM+Singlet.
No exotic H decay, no H-S mixing, no EWPO, …

Two regions with strong EWPT

Only Higgs Portal signatures:
h*→SS direct production
Higgs cubic coupling
σ(Zh) deviation (> 0.6% @ TLEP)

Curtin, Meade, Yu, arXiv:1409.0005



⇒ Appearance of first "no-lose" arguments for classes of compelling scenarios of new physics

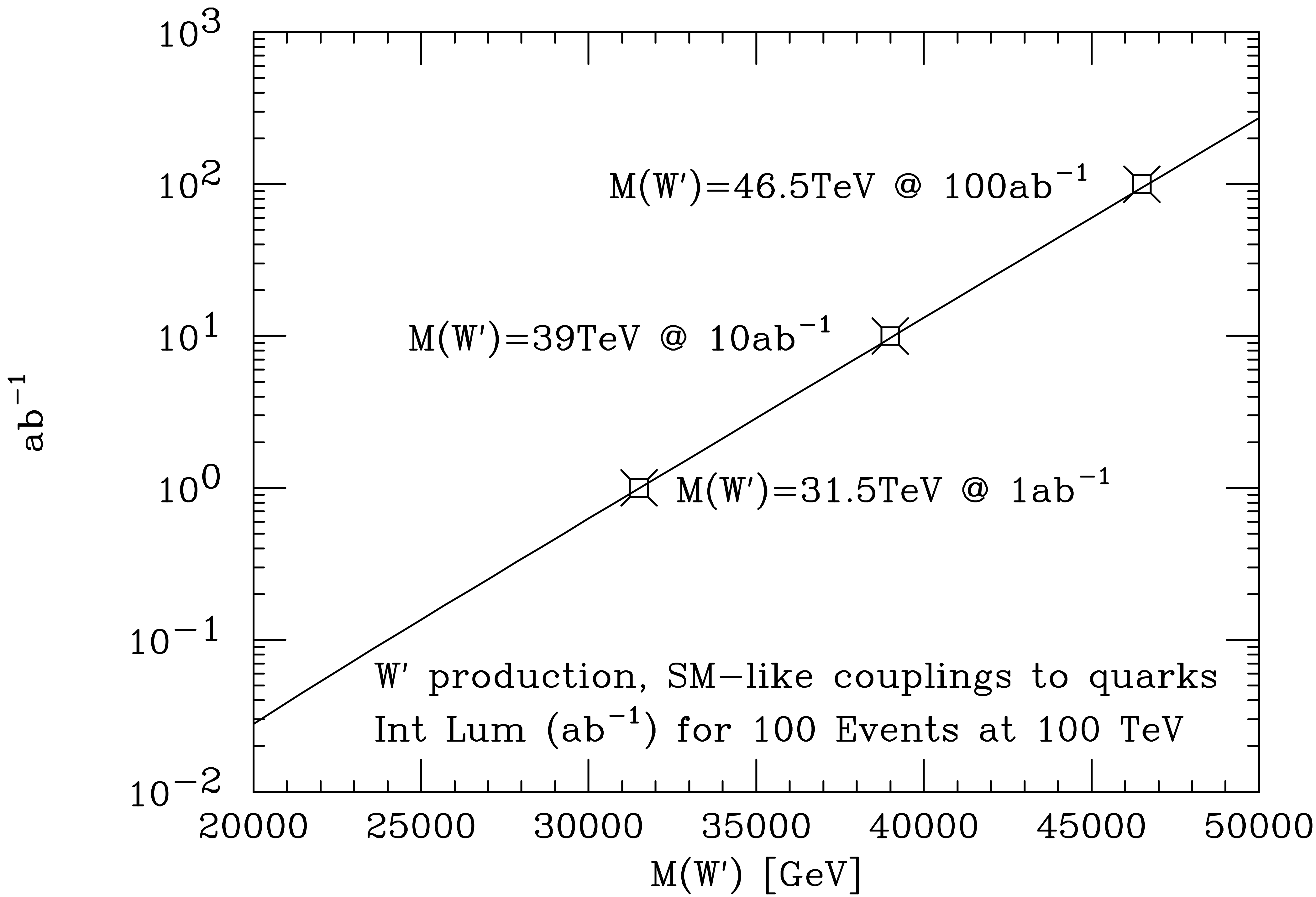
Direct discovery potential at the highest masses

at high mass, the reach of FCC-hh searches for BSM phenomena like Z', W', SUSY, LQs, top partners, etc.etc. scales trivially by ~5-7, depending on total luminosity …

New gauge bosons discovery reach

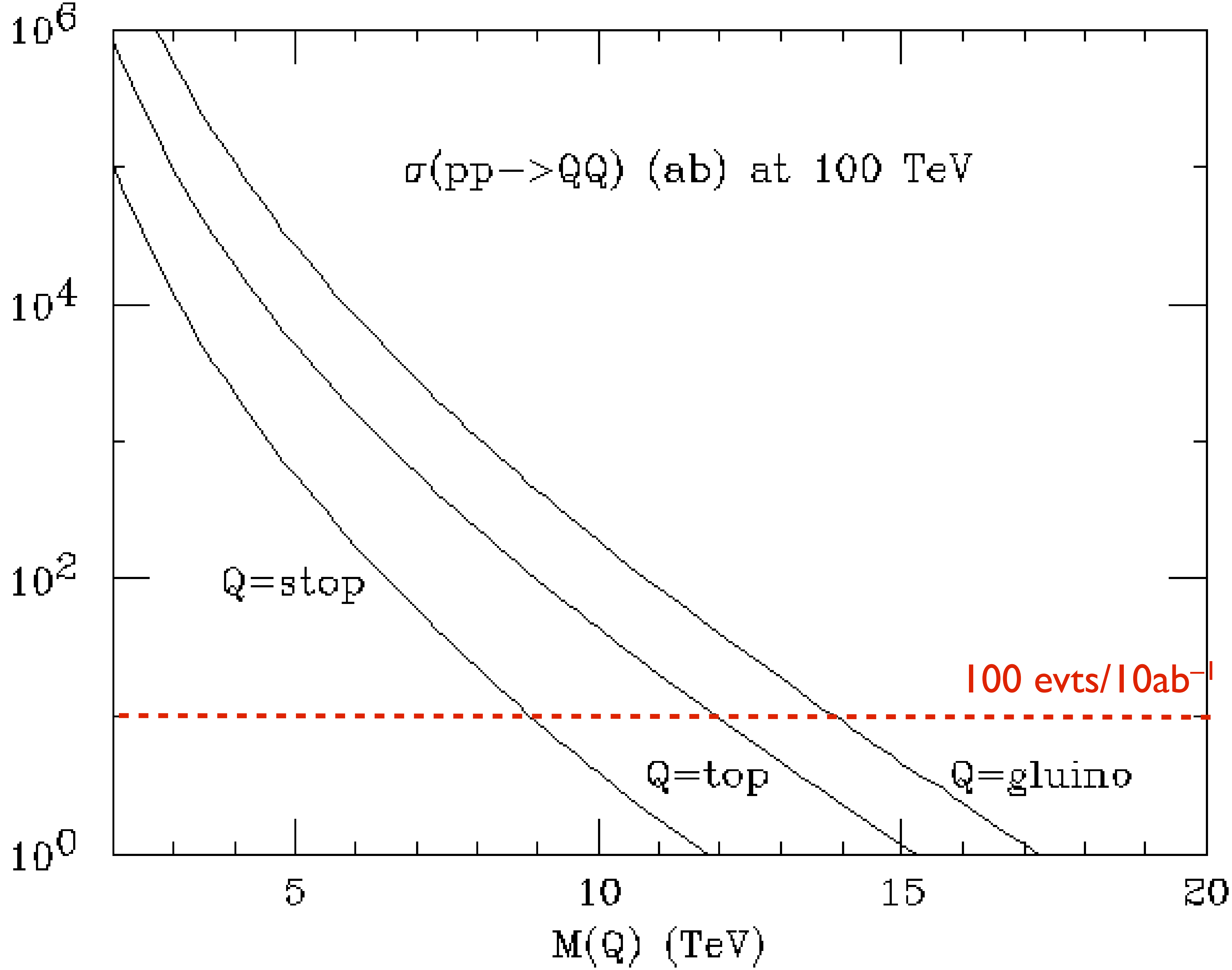
Example: **W' with SM-like couplings**

NB For SM-like Z', $\sigma_{Z'}$ BR_{lept} ~ 0.1 x $\sigma_{W'}$ BR_{lept} , ⇒ rescale lum by ~ 10



At L=O(ab^{-1}), Lum x 10 ⇒ ~ M + 7 TeV

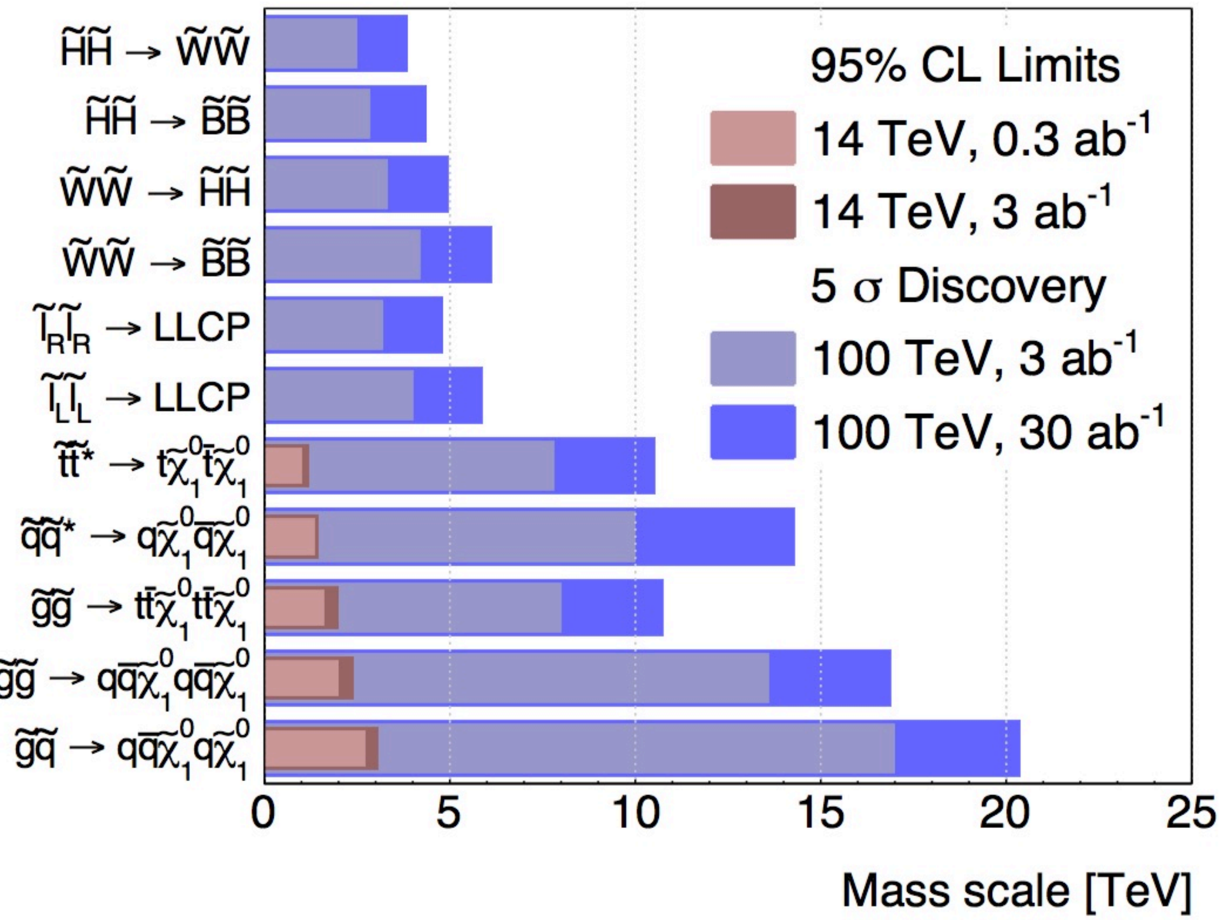
Discovery reach for pair production of strongly-interacting particles

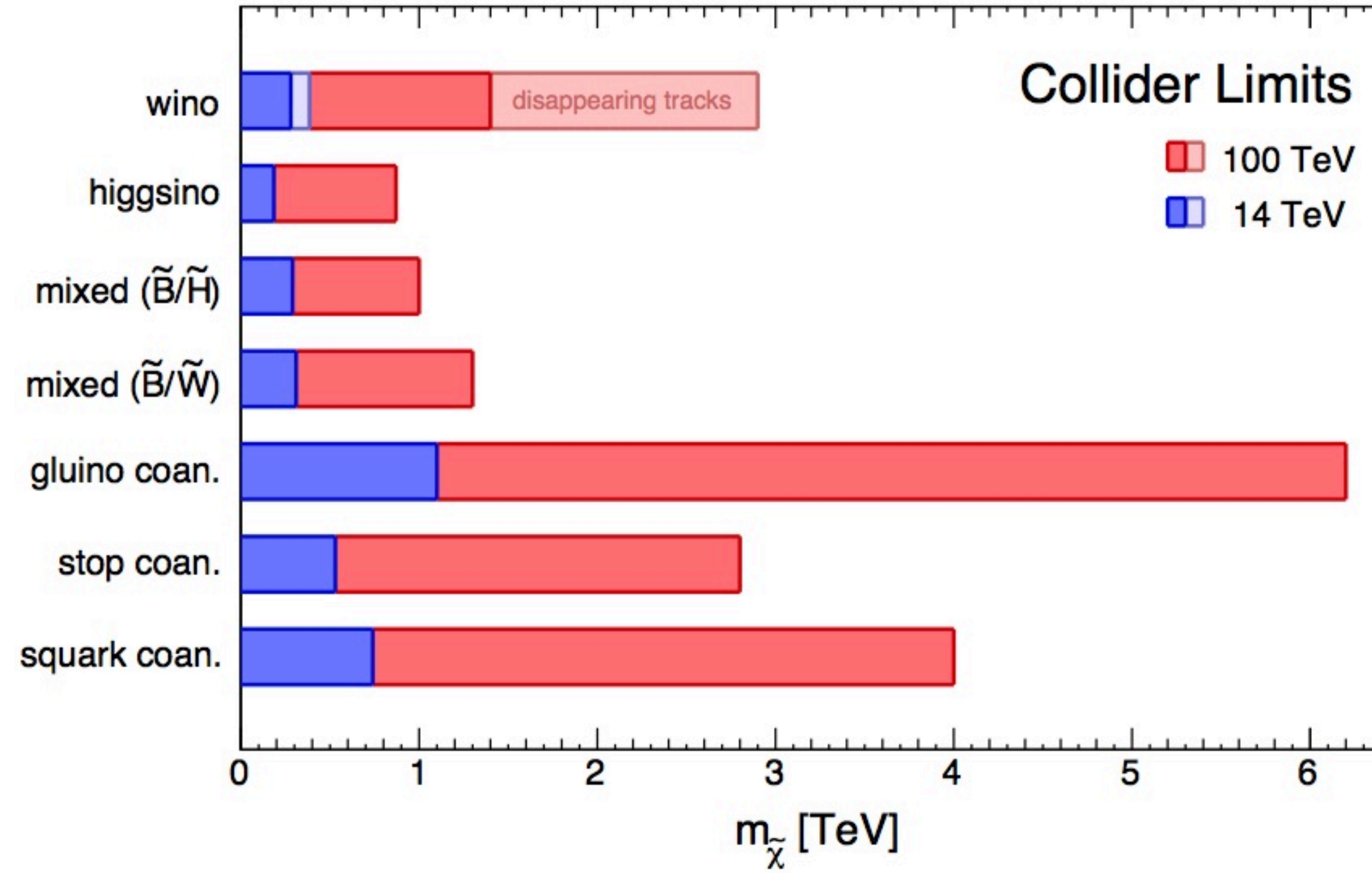


Dark Matter

- DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).
- More in general, no experiment can guarantee an answer to the question ”what is DM?”
- Scenarios in which DM is a WIMP are however compelling and theoretically justified
- **We would like to understand whether a future collider can answer more specific questions, such as:**
  - do WIMPS contribute to DM?
  - can WIMPS, detectable in direct and indirect (DM annihilation) experiments, be discovered at future colliders? Is there sensitivity to the explicit detection of DM-SM mediators?
  - what are the opportunities w.r.t. new DM scenarios (e.g. interacting DM, asymmetric DM, ...)?

SUSY and DM reach at 100 TeV





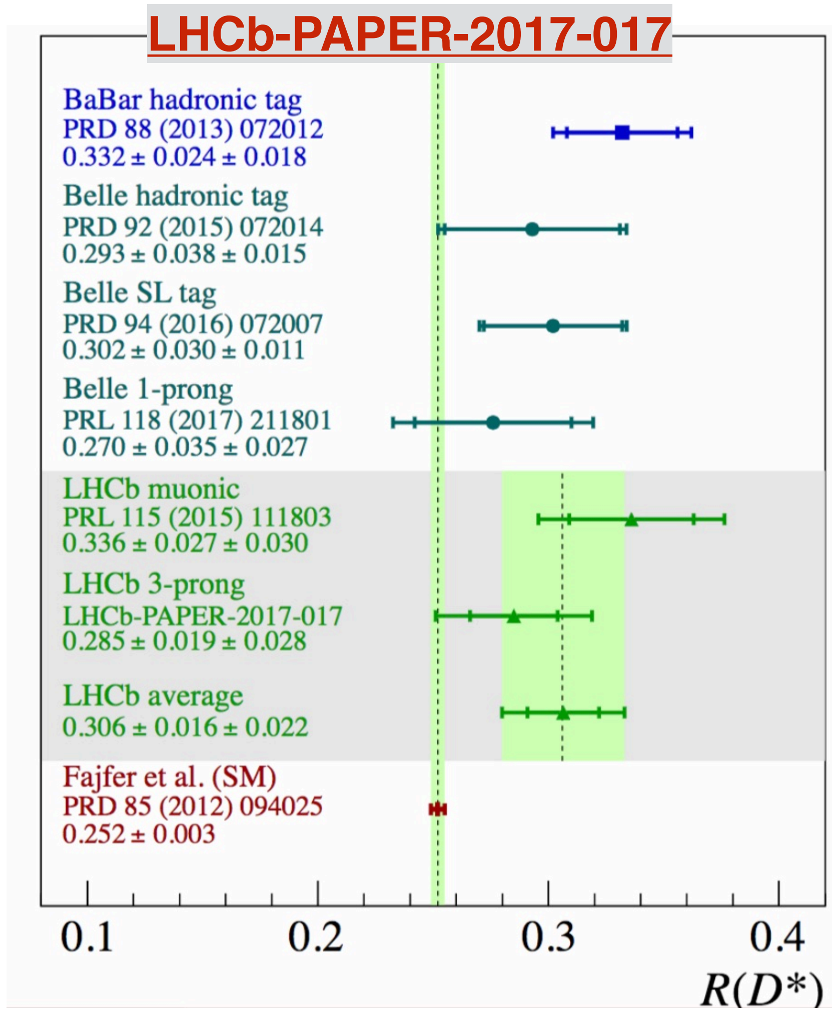
$$M_{\mathrm{WIMP}} \leq 1.8\ \mathrm{TeV}\left(\frac{g^2}{0.3}\right)$$

possibility to find (or rule out) thermal WIMP DM candidates

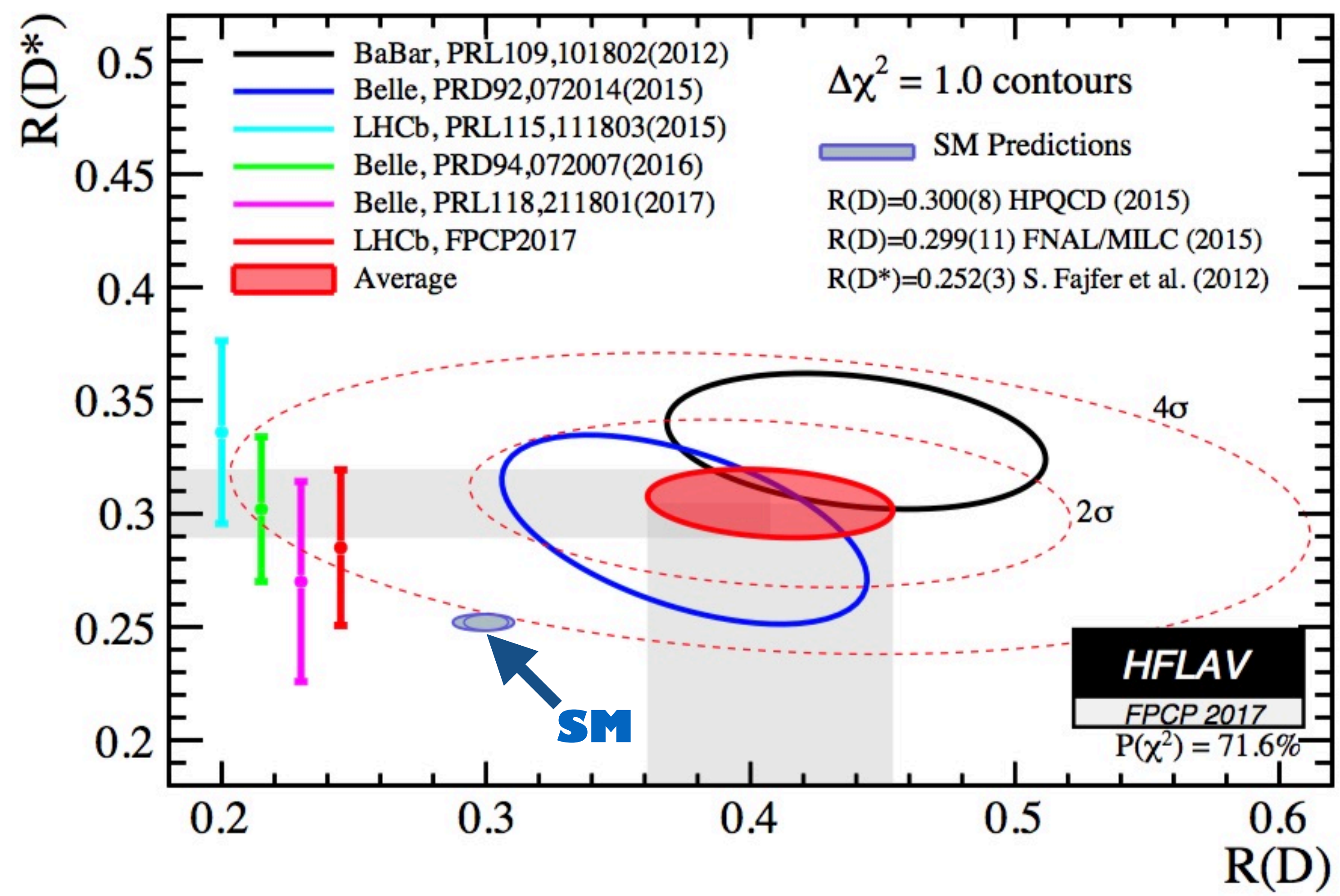
Flavour anomalies at LHC & Bfact's

$b \to c \ell \nu$

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)} \tau \nu)}{BR(B \to D^{(*)} \mu \nu)}$$



Overall combination of R(D) and R(D*) is 4.1σ from SM



$b \to s \ell \ell$

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)} \mu\mu)}{BR(B \to K^{(*)} ee)}$$

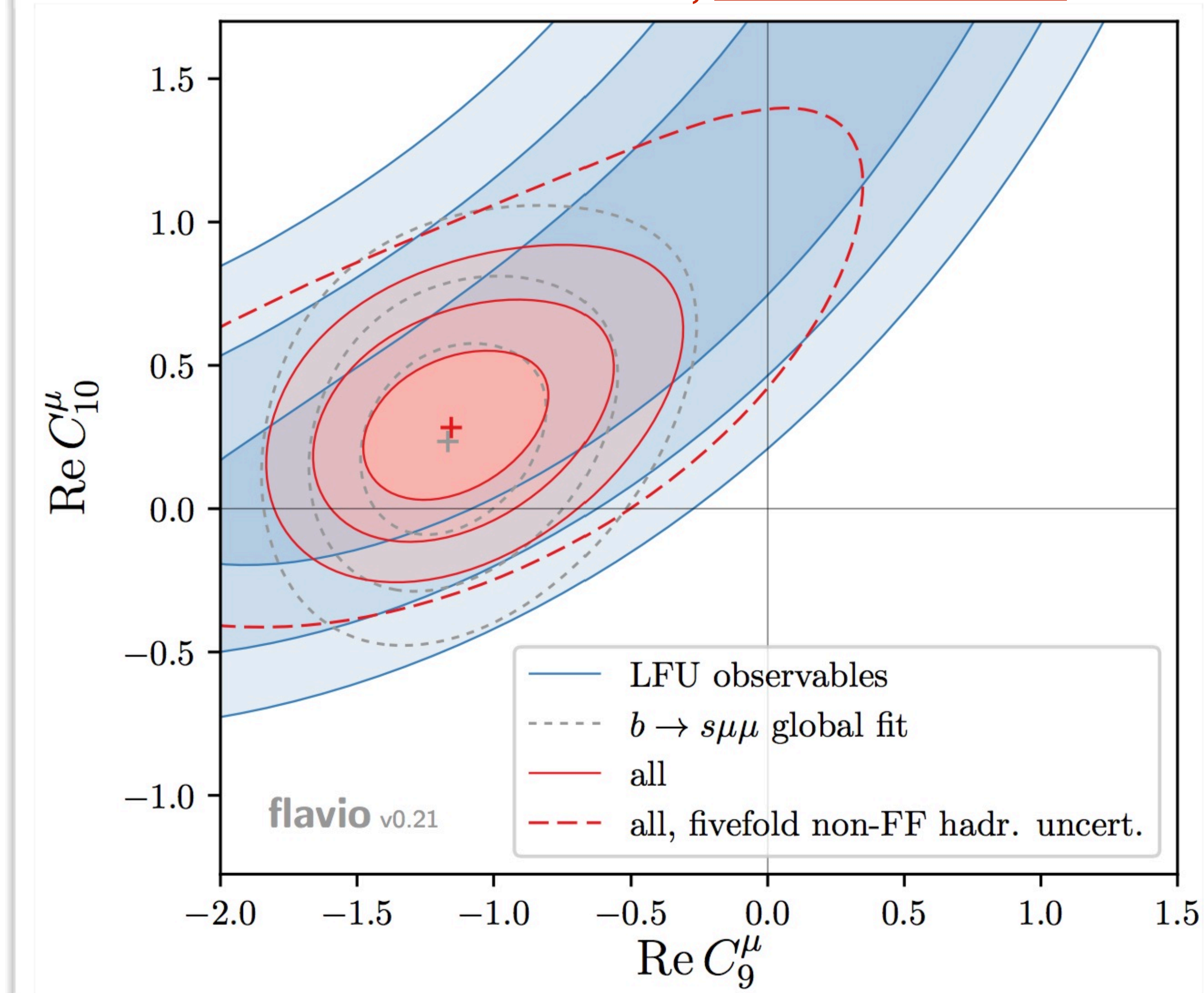
m_{ll} [mass range]	SM	Exp.
$R_K{}^{[1-6]}$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_{K^*}{}^{[1.1-6]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.069} \pm 0.047$
$R_{K^*}{}^{[0.045,1.1]}$	0.91 ± 0.03	$0.660^{+0.110}_{-0.070} \pm 0.024$

LHCb, PRL 113 (2014) 151601 , arXiv:1705.05802

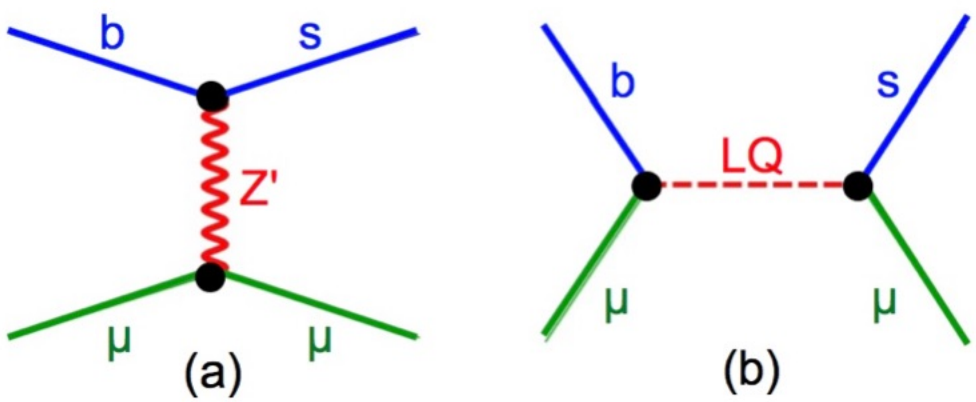
Example of EFT interpretation of R_K

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

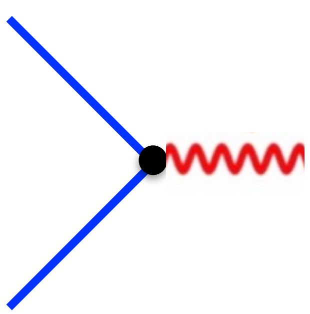
Altmannshoffer et al, arxiv:1704.05435



Possible explicit realizations:

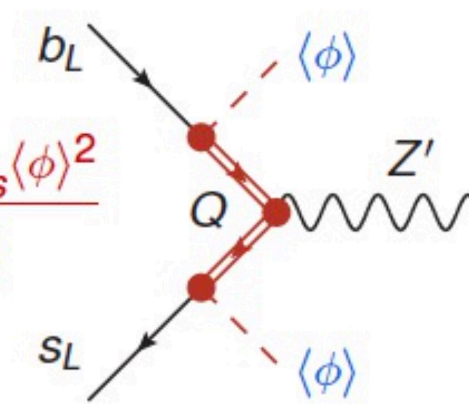


where, e.g. ,



$\Rightarrow$

$$\frac{g' Y_{Qb} Y^*_{Qs} \langle\phi\rangle^2}{2m_Q^2}$$



Upper limits on Z' and Leptoquark masses are model-dependent, and constrained also by other low-energy flavour phenomenology, but typically lie in the range of 1→O(10) TeV

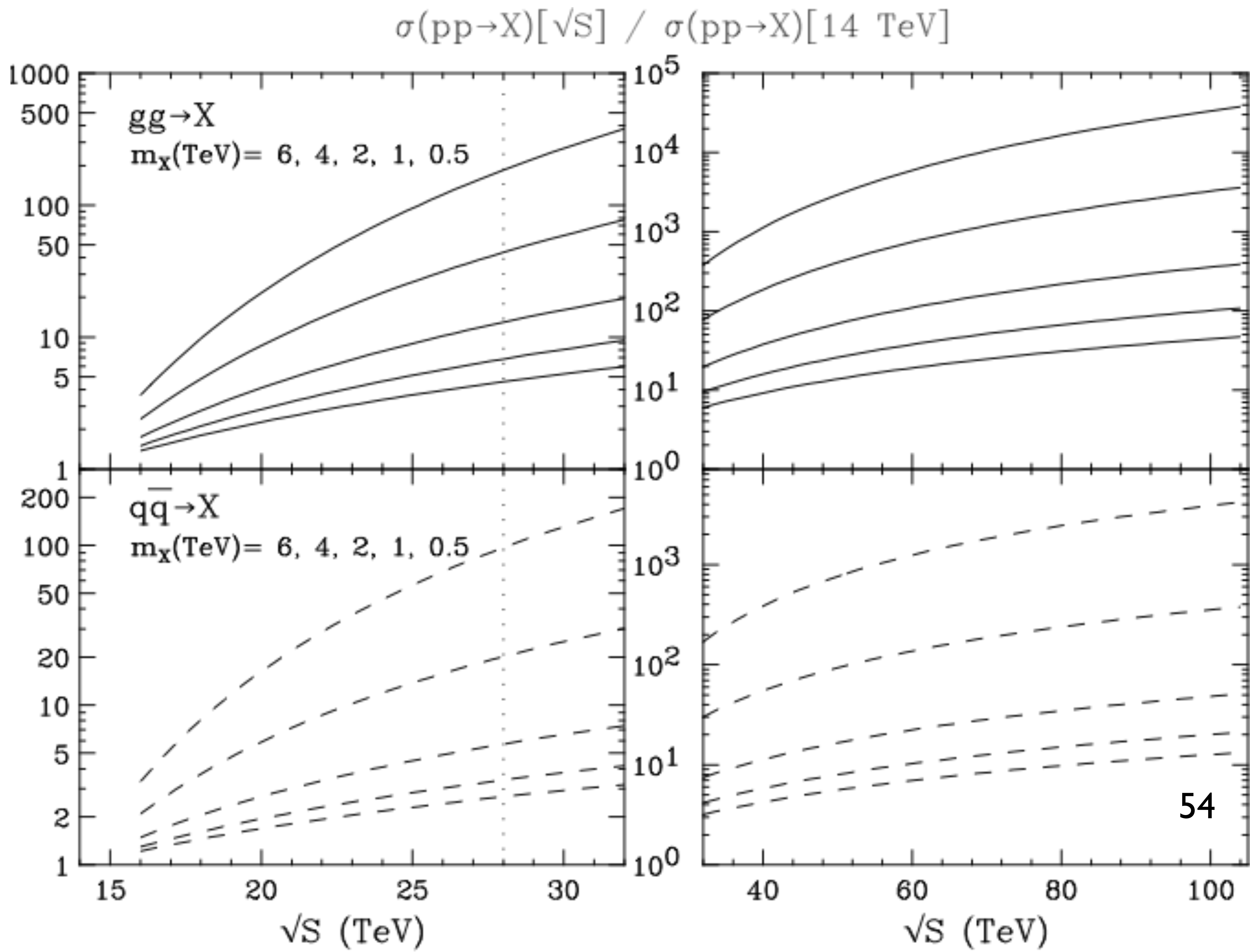
⇒ if anomalies confirmed, we may want a no-lose theorem to identify the next facility!

100 TeV ?

200 TeV ?

27 TeV in the LHC tunnel, replacing current magnets with those developed for FCC ?

Evolution, with beam energy, of scenarios with the discovery of a new particle at the LHC

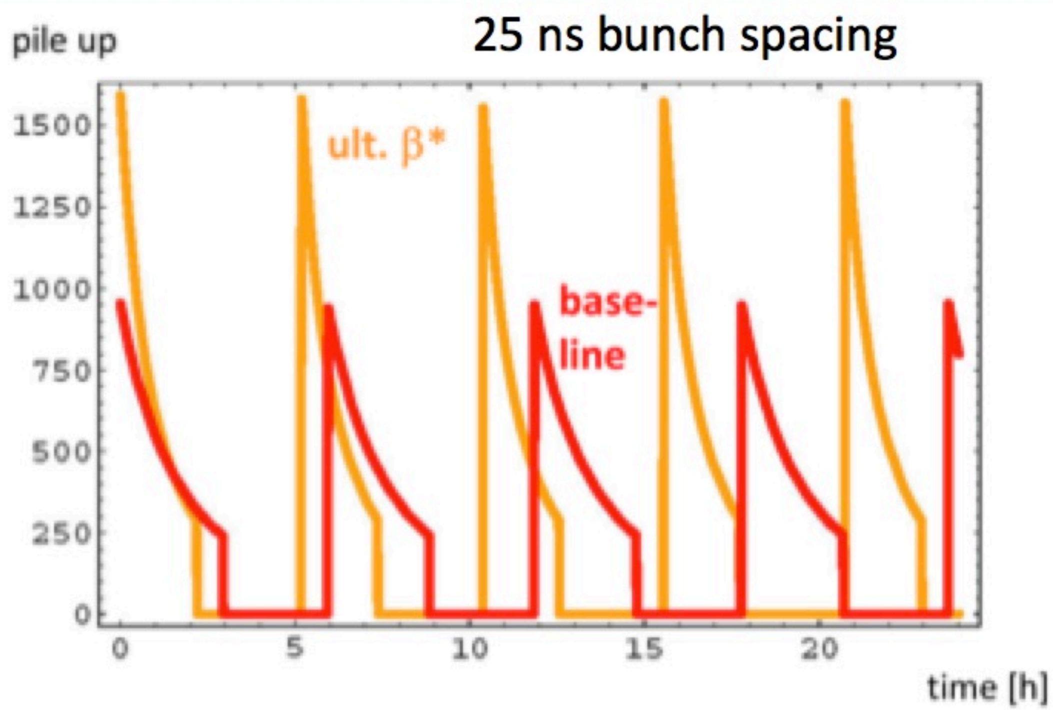


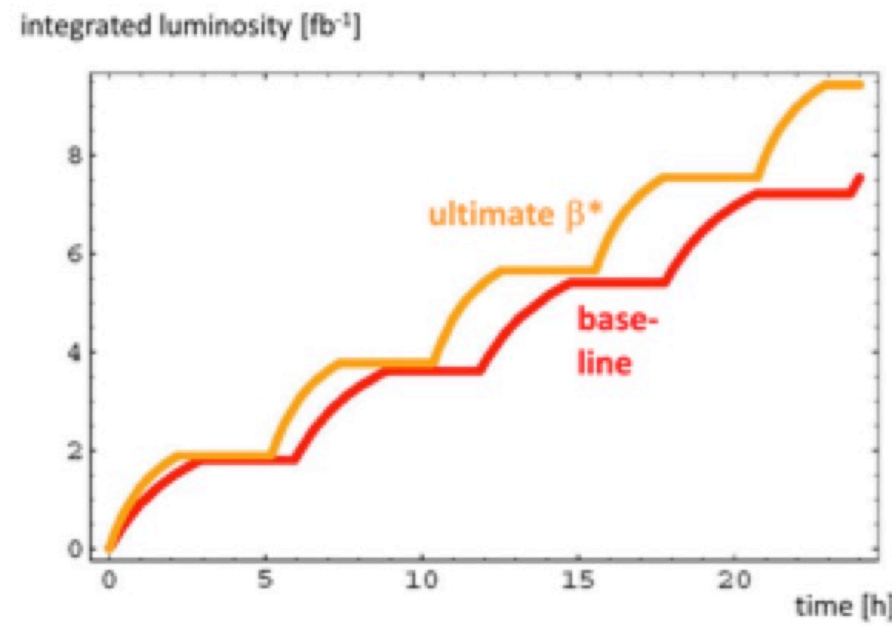
Possible questions/options

- If m_X ~ 6 TeV in the gg channel, rate grows x 200 @28 TeV:
  - Do we wait 40 yrs to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?
  - Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$) ?
  - .... and the answers may depend on whether we expect partners of X at masses $\gtrsim 2m_X$ ($\Rightarrow$ *28 TeV would be insufficient ....*)
- If m_X ~ 0.5 TeV in the qqbar channel, rate grows x10 @100 TeV:
  - Do we go to 100 TeV, or push by x10 $\int L$ at LHC?
  - Do we build CLIC?
- etc.etc.

HE-LHC (27 TeV), prelim performance estimates

HE-LHC: pile up & performance





with 160 days of physics, 70% availability, 3 h turnaround time

β^*=25 cm: 920 fb^{-1}/year

β^*=15 cm: 1100 fb^{-1}/year

pile up of 1000 or shorter (e.g. 5 ns) bunch spacing – what is easier?

M. Benedikt, S. Fartoukh, F. Zimmermann

=> O(15 ab^{-1}) over 15-20 years

Systematics studies* of the full physics potential at O(28) TeV, with O(15 ab^{-1}), need to be carried out

* except for straightfwd mass-reach extrapolations from LHC

E.g. HH at 28 TeV (back of the envelope)

σ_{HH}(28 TeV)/σ_{HH}(14 TeV) ~ 4 Lum(28)~ 4 Lum(14 TeV)

=> N_{HH}(28) ~ 16 N_{HH}(14)

=> $\delta\lambda_{HHH}$ (28) ~ $\delta\lambda_{HHH}$ (HL-LHC) / 4 ~ 10%

Expect to carry out an overall evaluation of the physics potential during 2018 (in the context of the HL-LHC Physics workshop, https://indico.cern.ch/event/647676)

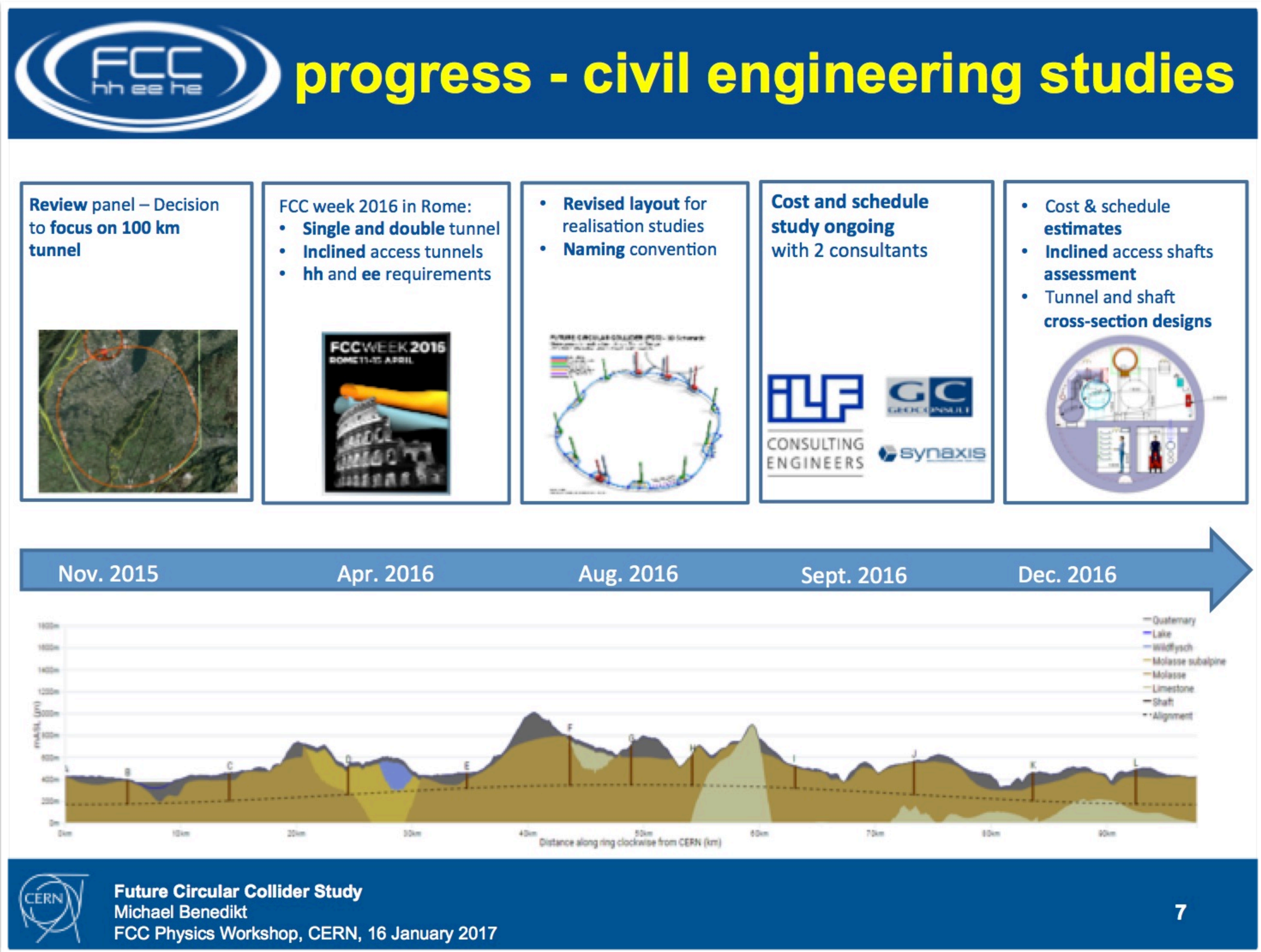
What does the HE-LHC entail?

- **Necessary:**
  - empty the tunnel (more time & $s than removing LEP)
  - full replacement of the magnets (today's cost ~4xLHC. First prototypes in ~2026)
  - upgrade of RF, cryogenics, collimation, beam dumps, …
- **Very likely:**
  - major upgrade of SPS, if need to inject at O(1 TeV) (magnets, RF, transfer lines, cryo if SC, …)
  - major overhaul of detectors (radiation damage after HL-LHC, use of new technologies)

=> it's like building the LHC ex-novo

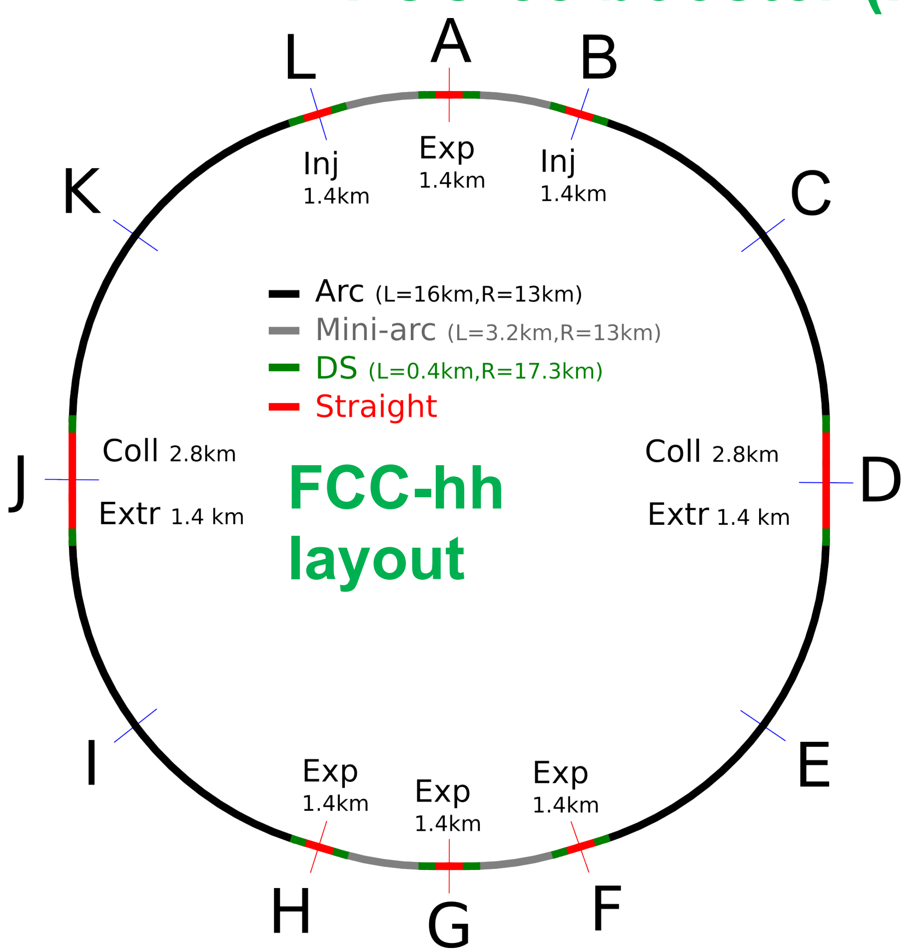
- very unlikely to be cheaper …
- … but not incompatible with a ~constant CERN budget
- nevertheless feasibility to be proven (eg magnets bigger than LHC's: will they fit in the tunnel ??)

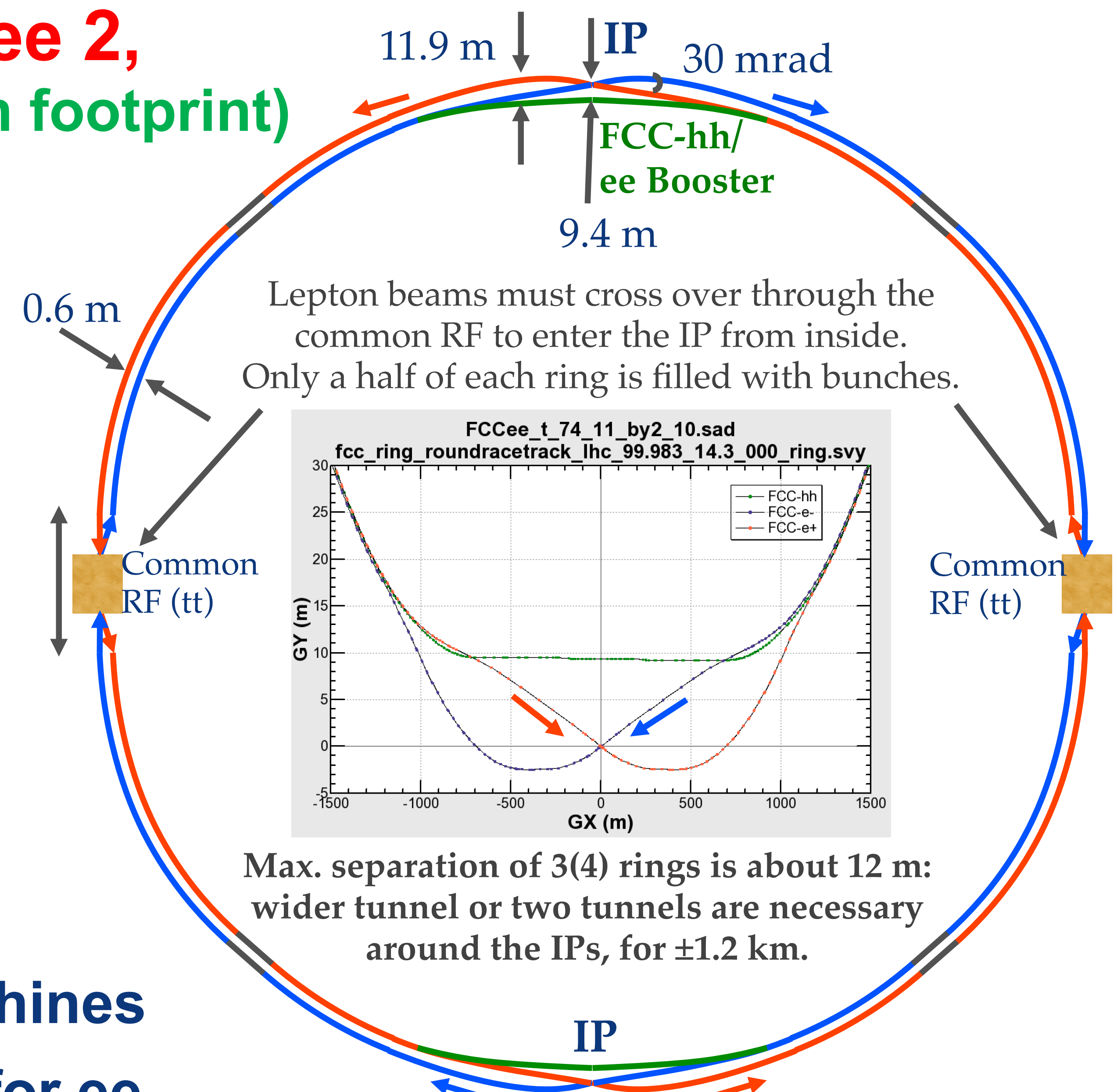
Snapshots of the status of the FCC studies


FCC
hh ee he
progress - civil engineering studies
Review panel – Decision to focus on 100 km tunnel
FCC week 2016 in Rome:
• Single and double tunnel
• Inclined access tunnels
• hh and ee requirements
FCCWEEK 2016
ROME 11-15 APRIL
• Revised layout for realisation studies
• Naming convention
Cost and schedule study ongoing with 2 consultants
ILF
CONSULTING ENGINEERS
GC
synaxis
• Cost & schedule estimates
• Inclined access shafts assessment
• Tunnel and shaft cross-section designs
Nov. 2015
Apr. 2016
Aug. 2016
Sept. 2016
Dec. 2016
Quaternary
Lake
Wildflysch
Molasse subalpine
Molasse
Limestone
Shaft
Alignment
Distance along ring clockwise from CERN (km)
CERN
Future Circular Collider Study
Michael Benedikt
FCC Physics Workshop, CERN, 16 January 2017
7

Common layouts for hh & ee

FCC-ee 1, FCC-ee 2,
FCC-ee booster (FCC-hh footprint)



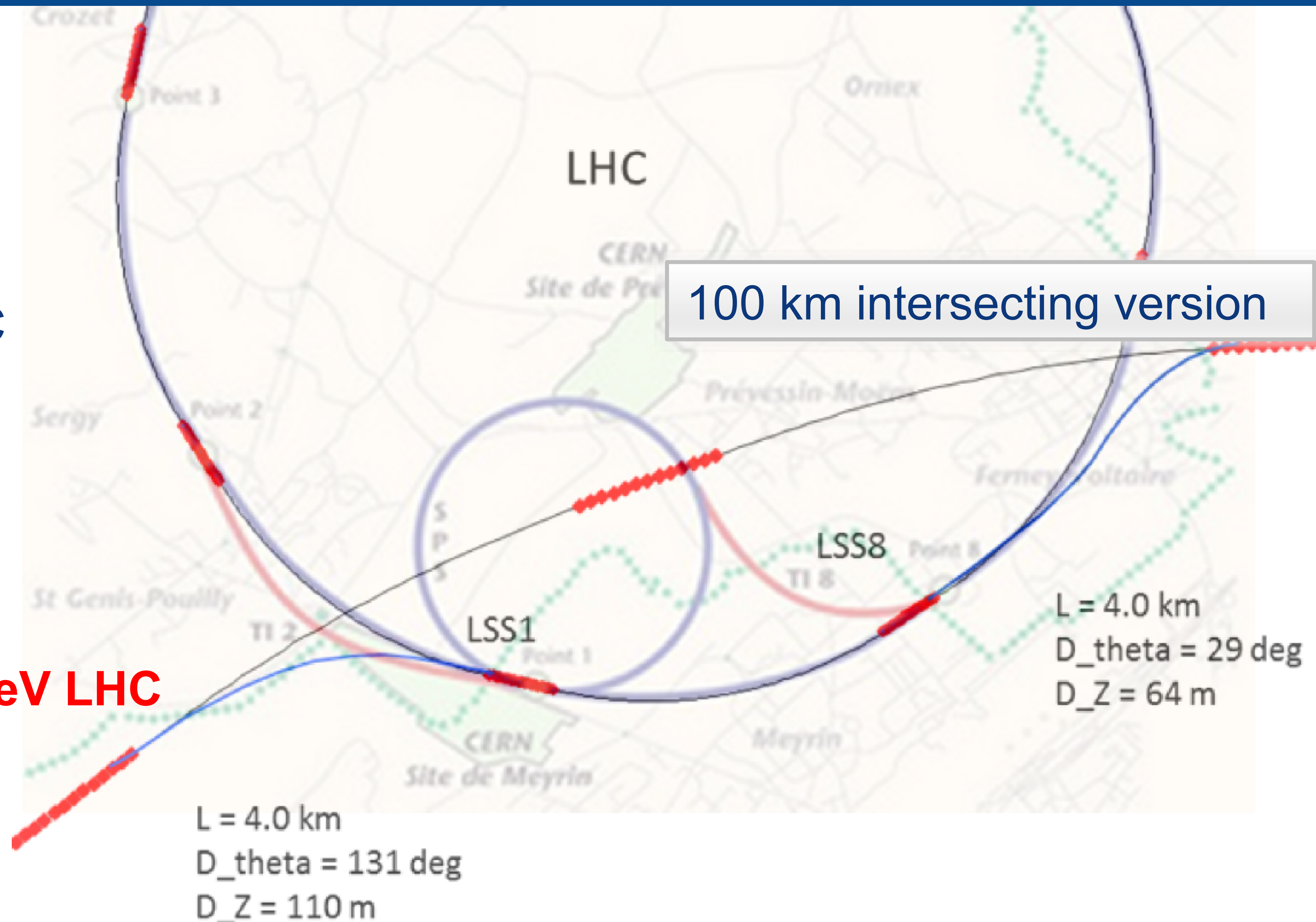


- 2 main IPs in A, G for both machines
- asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector

FCC-hh injector studies

Injector options:

- SPS → LHC → FCC
- SPS/$SPS_{upgrade}$ → FCC



Current baseline:

- Injection energy 3.3 TeV LHC

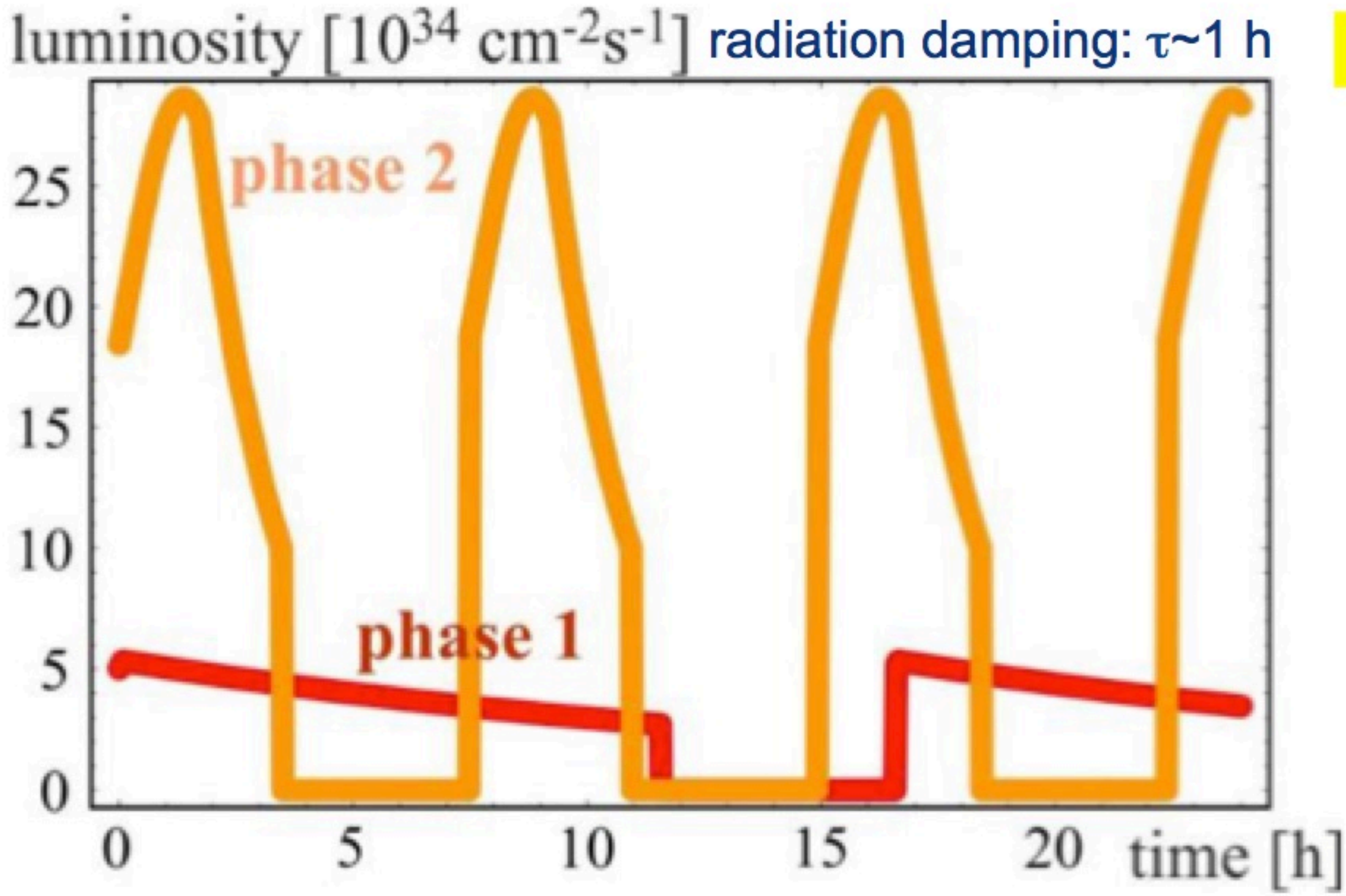
Alternative option:

- Injection around 1.5 TeV
- $SPS_{upgrade}$ could be based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp

FCC-pp collider parameters

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.20	0.55
normalized emittance [μm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	25	5	1
events/bunch crossing	170	1k (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

luminosity evolution over 24 h



PRST-AB 18, 101002 (2015)

for both phases:

beam current 0.5 A, unchanged!

total synchrotron radiation power ~5 MW.

phase 1: β^*=1.1 m, ξ_{tot}=0.01, t_{ta}=5 h, 250 fb^{-1} / year

phase 2: β^*=0.3 m, ξ_{tot}=0.03, t_{ta}=4 h, 1000 fb^{-1} / year

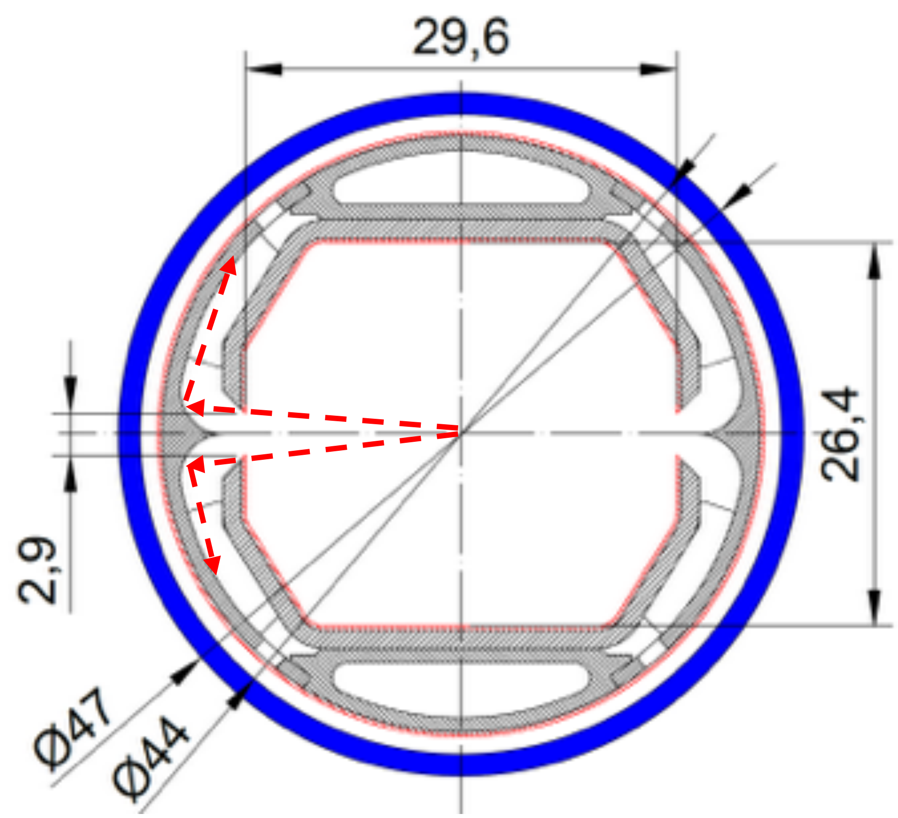
First FCC Physics Workshop
Frank Zimmermann
CERN, 16-20 January 2017

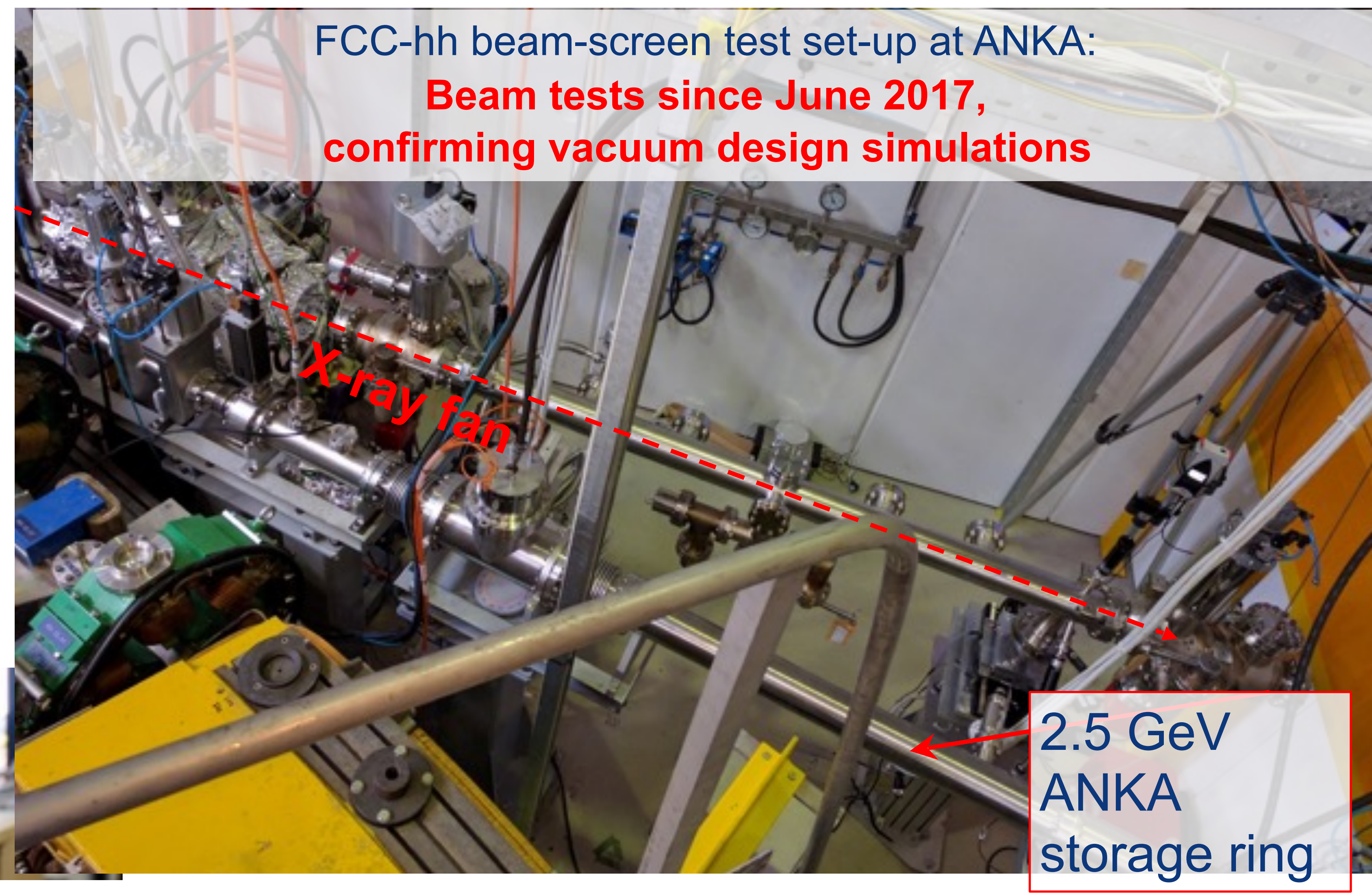
look @ Zimmermann's slides for many more details, 25ns vs 5ns, etc

FCC-hh cryogenic beam vacuum system

Synchrotron radiation **(~ 30 W/m/beam (@16 T field)** (LHC <0.2W/m) **~ 5 MW total load in arcs**

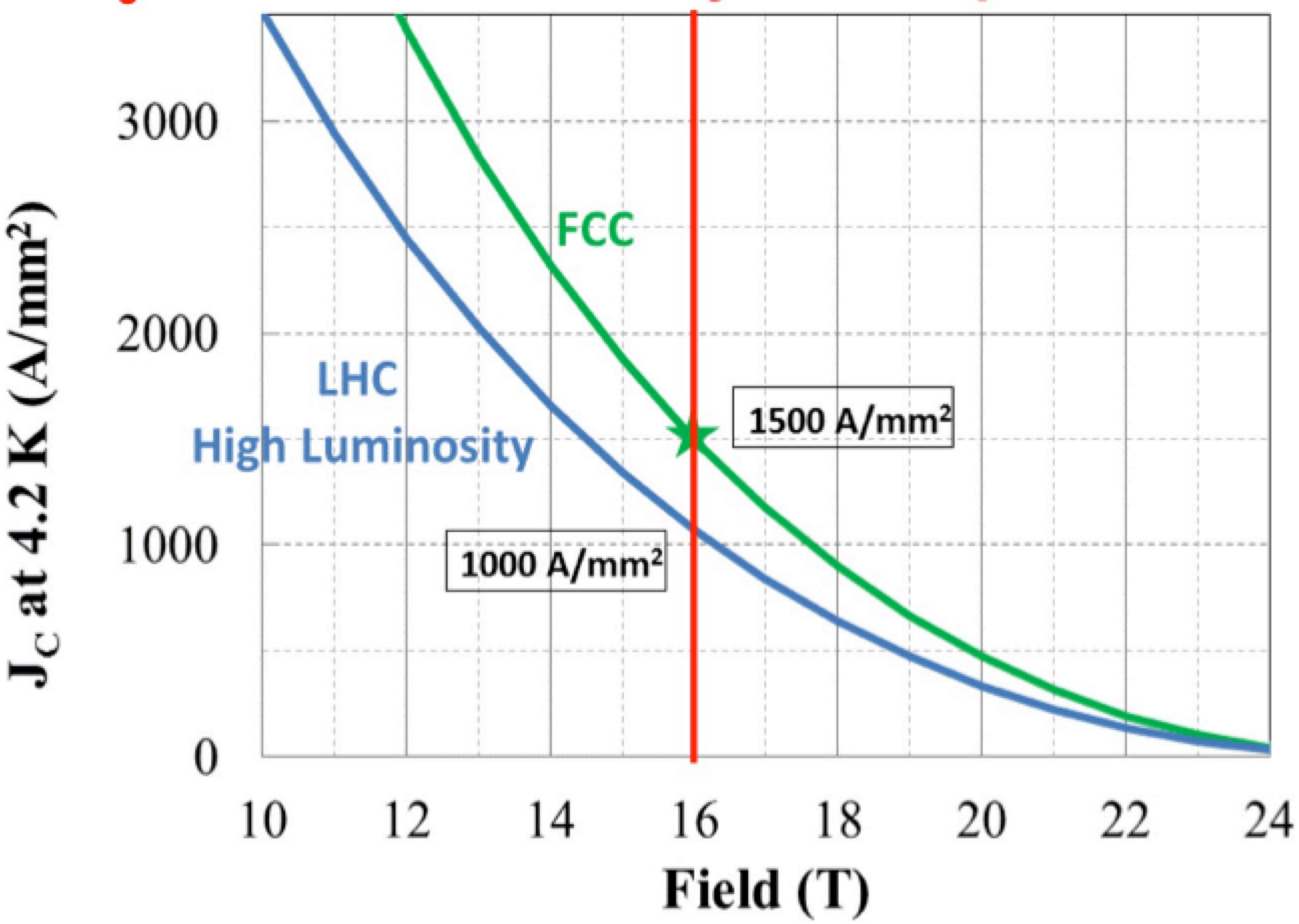
- **Absorption of synchrotron radiation at ~50 K** for cryogenic efficiency (**5 MW →100 MW cryoplant**)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.





Nb_3Sn conductor development program

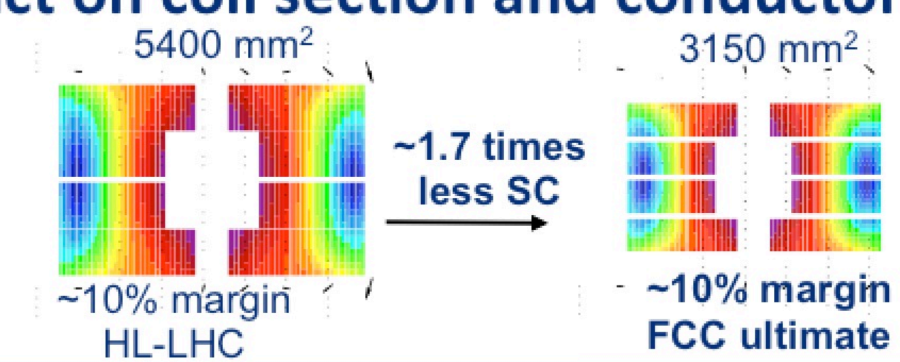
Nb_3Sn is one of the key cost & performance factors for FCC-hh / HE-LHC



Main development goals:

- J_c increase (16T, 4.2K) > 1500 A/mm² i.e. 50% increase wrt HL-LHC wire
- Reference wire diameter 1 mm
- Potentials for large-scale production and cost reduction

Impact on coil section and conductor mass



Collaborations FCC Nb_3Sn program

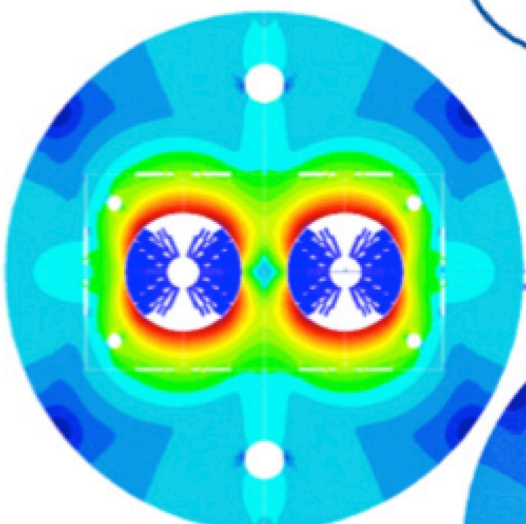
Established worldwide activities for Nb3Sn development:

- **Procurement of state-of-the-art conductor for protoyping:**
  - ➢ **Bruker-OST**– **European/US**
- **Stimulation of conductor development with regional industry:**
  - ➢ **CERN/KEK** – **Japanese** contribution. Japanese **industry** (JASTEC, Furukawa, SH Copper) and laboratories (Tohoku Univ. and NIMS).
  - ➢ **CERN/Bochvar High-technology Research Inst.** – **Russian** contribution. Russian **industry** (TVEL) and laboratories
  - ➢ **CERN/KAT** – **Korean** **industrial** contribution
- **Characterization of conductor & research with universities:**
  - ➢ **Europe: Technical Univ. Vienna, Geneva University, University of Twente**
  - ➢ **Applied Superconductivity Centre** at Florida State University

16 T dipole design activities and options

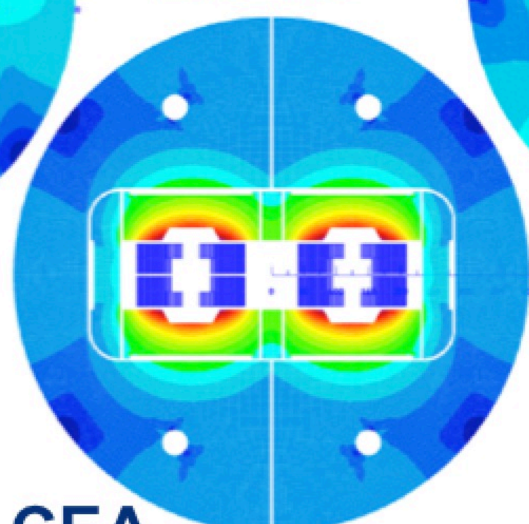
H2020 EuroCirCol
A key to New Physics

Cos-theta



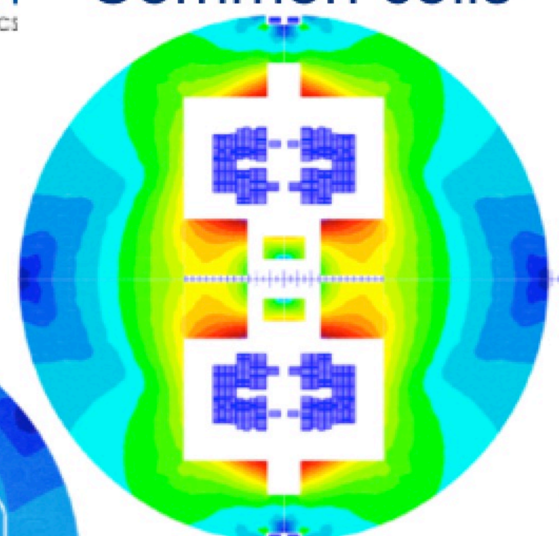
INFN

Blocks



CEA

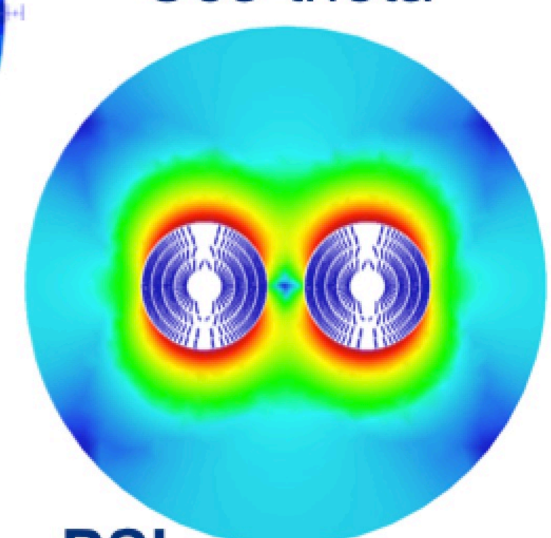
Common coils



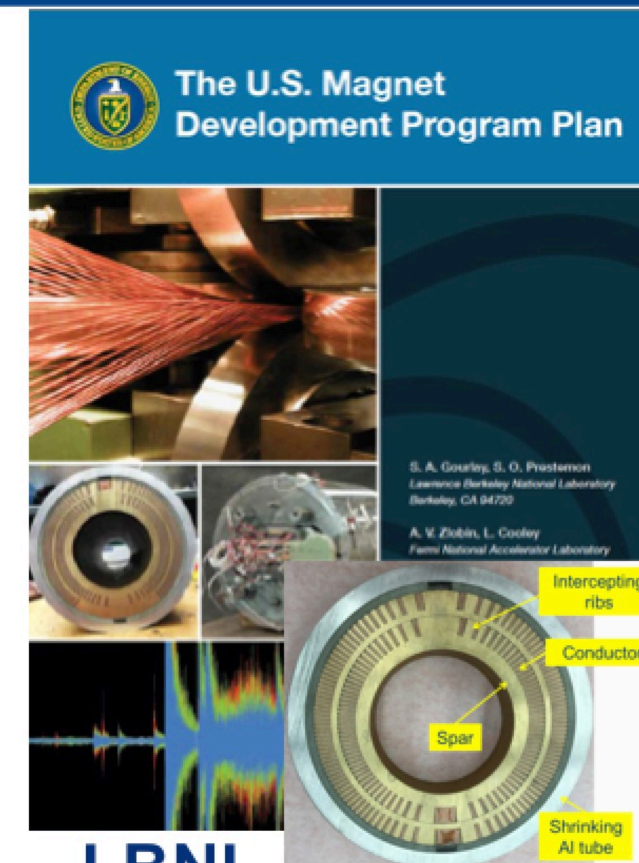
CIEMAT

Swiss contribution

Canted Cos-theta

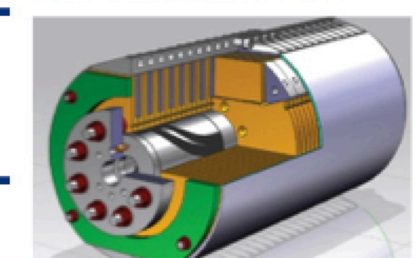


PSI



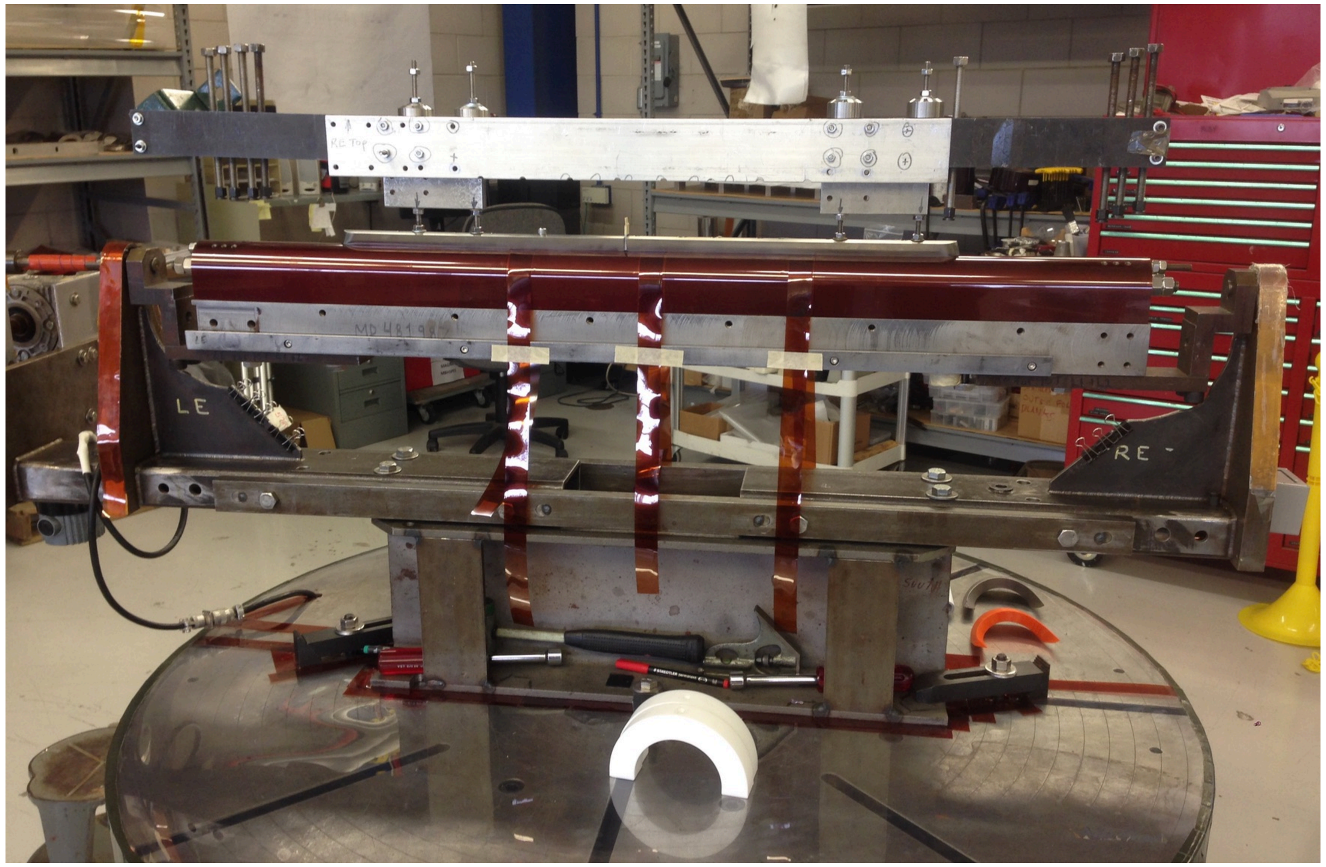
LBNL

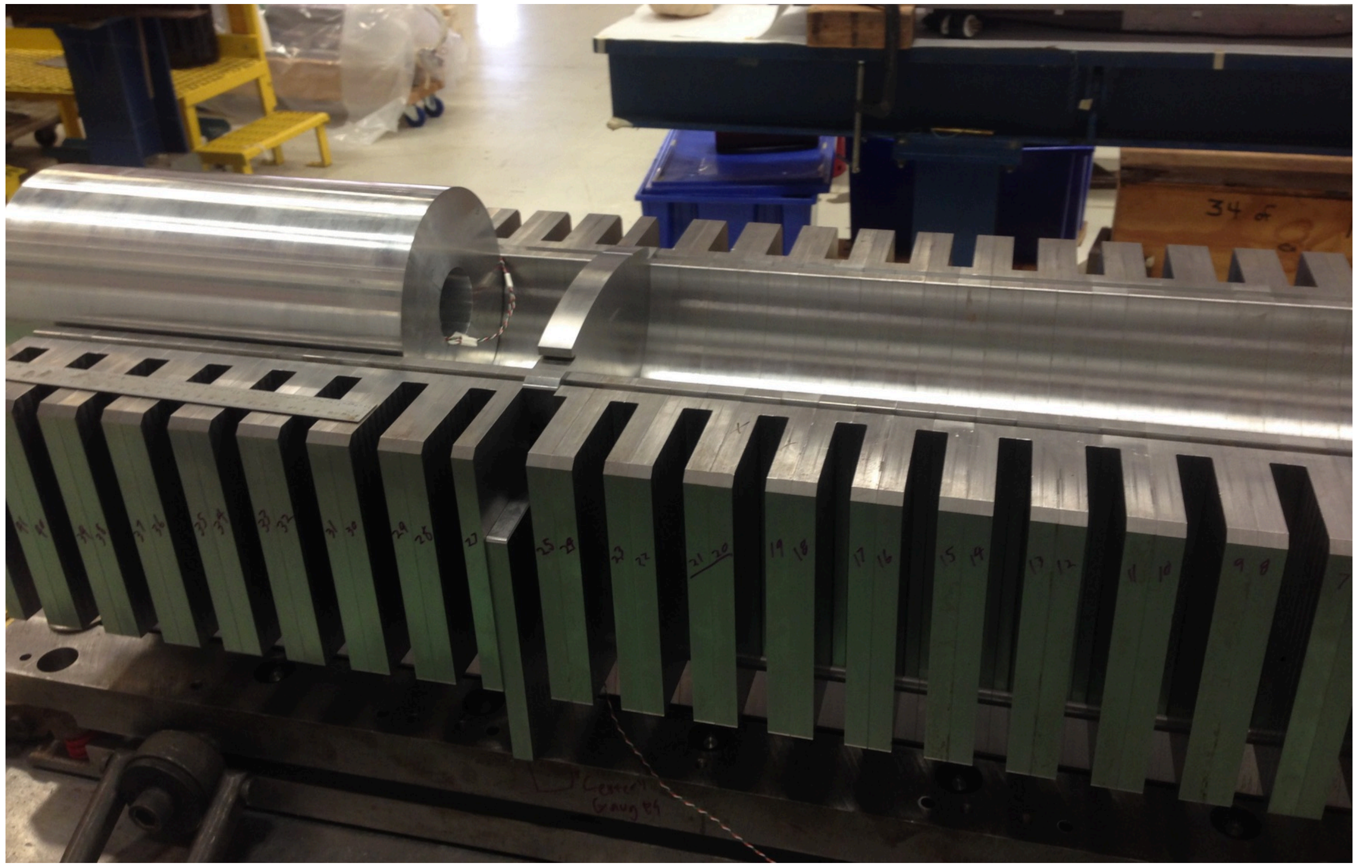
FNAL

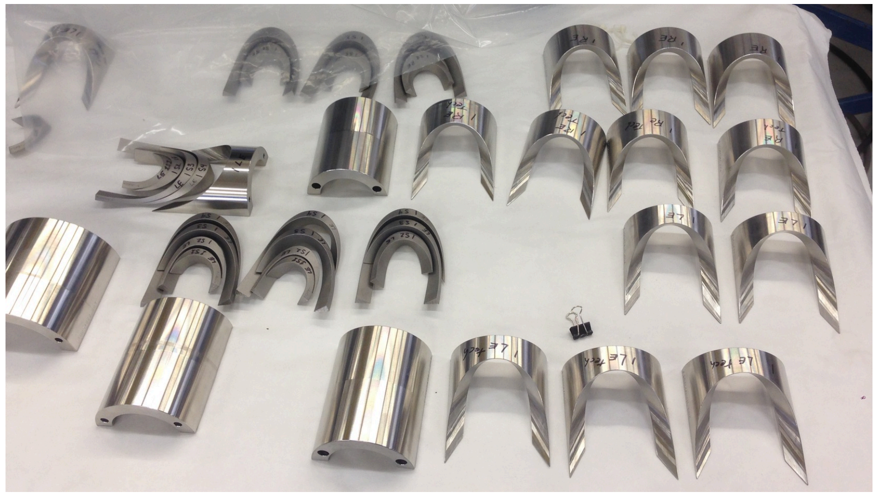


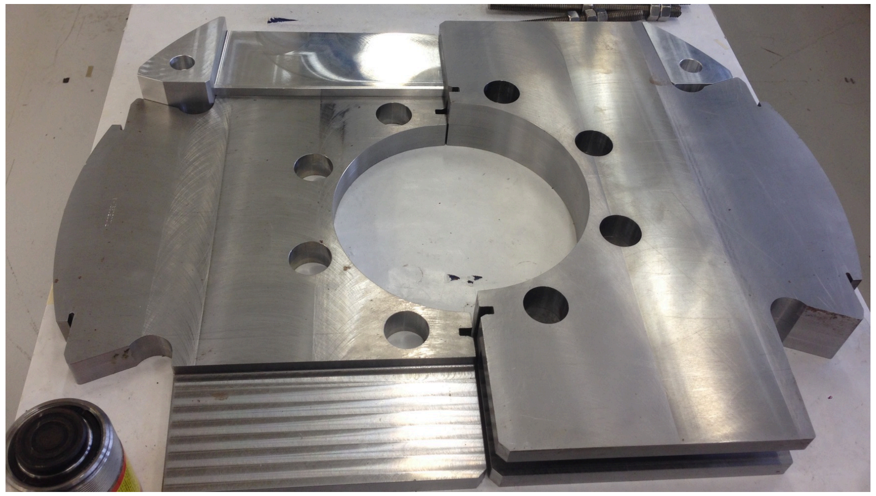
Short model magnets (1.5 m lengths) will be built from 2017 - 2021

15T dipole prototyping at FNAL (60mm aperture, L=1m)

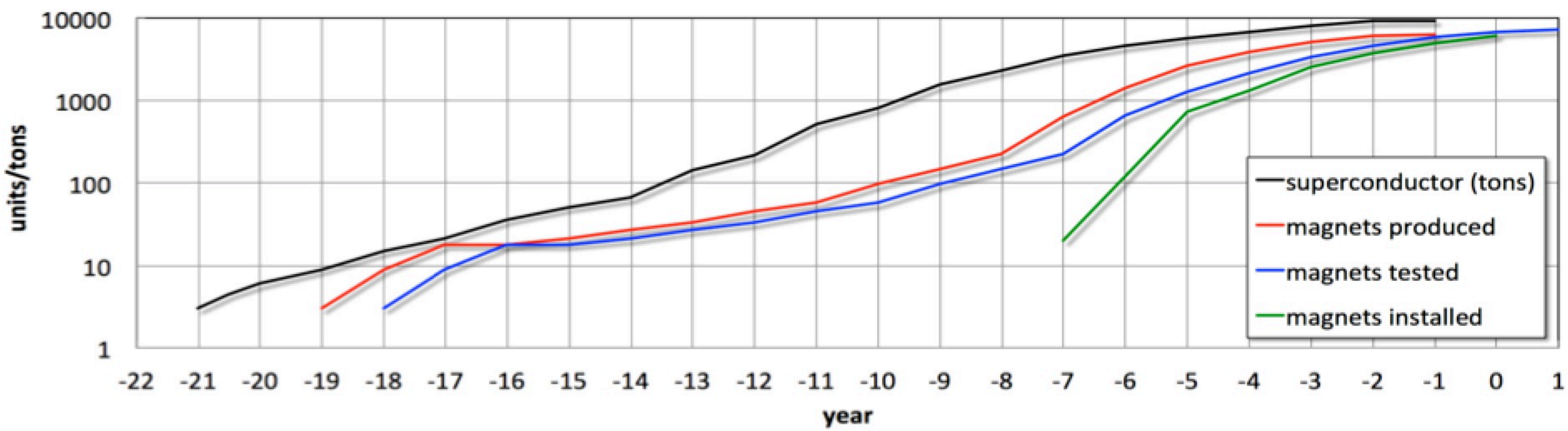






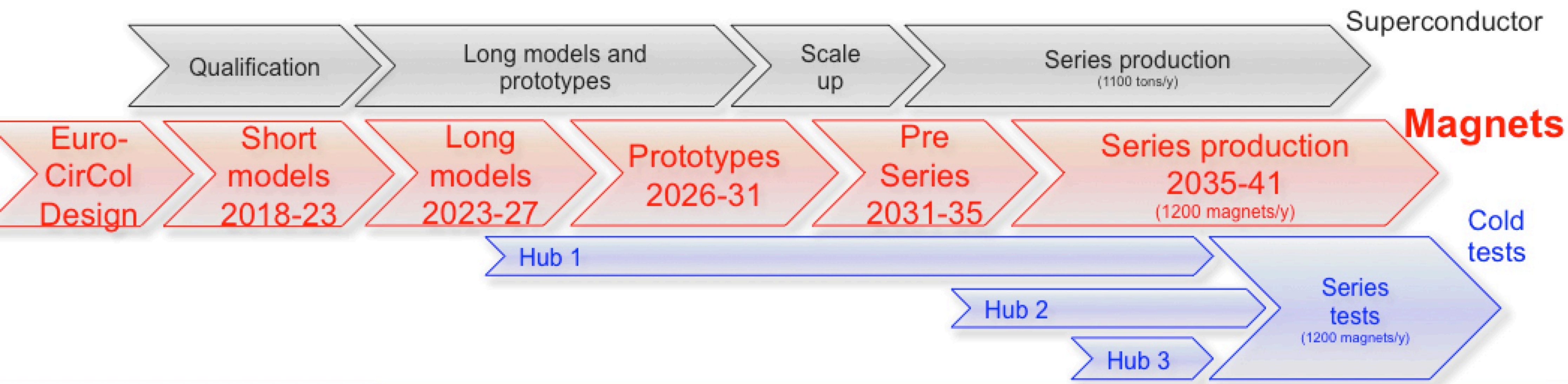


16 T magnet R&D schedule



Total duration of magnet program:

~20 years



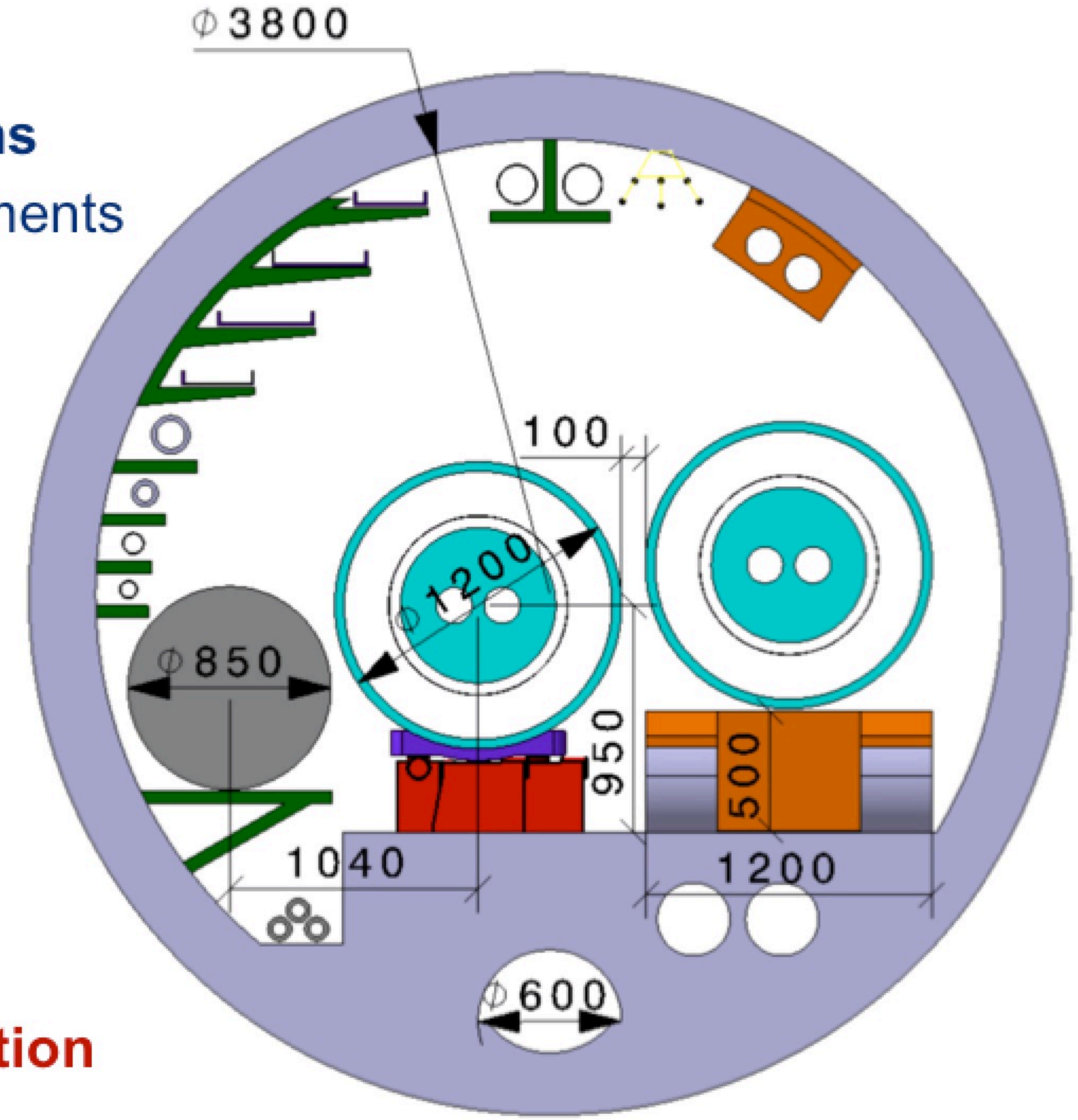
Would follow on HL-LHC Nb_3Sn program with long models with industry from 2023/24

HE-LHC integration aspects

Working hypothesis for HE LHC design:

No major CE modifications on machine tunnel and caverns

- Similar geometry and layout as LHC machine and experiments
- **Maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **Classical 16 T cryostat design based on LHC approach gives ~1500 mm diameter!**



Strategy: develop a single 16 T magnet, compatible with both HE LHC and FCC-hh requirements:

- **Allow stray-field and/or cryostat as return-yoke**
- **Optimization of inter-beam distance (compactness)**

→ Smaller diam. also relevant for FCC-hh cost optimization

Final remarks

- The accelerator performance, experimental ingenuity, and theoretical progress, make the LHC the most complete and reaching enterprise available today and in the near future to explore in depth physics at the TeV scale, with an immense discovery potential and still ample room for surprises
- The study of the SM will not be complete until we exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.
- As a possible complement to the mature ILC and CLIC projects, plans are underway to define the possible continuation of this programme after the LHC, with the same goals of thoroughness, precision and breadth that inspired the LEP/LHC era
- The physics case of a 100 TeV collider is very clear as a long-term goal for the field, simply because no other proposed or foreseeable project can have direct sensitivity to such large mass scales.
- Nevertheless, the precise route followed to get there must take account of the fuller picture, to emerge from the LHC as well as other current and future experiments in areas ranging from flavour physics to dark matter searches.

Additional material

Progress with FCC physics, 2016

- **FCC-ee events**: http://indico.cern.ch/category/5259/
  - Recent 2016 wshops:
    - 25 Nov *"LHC, FCC-ee, FCC-hh Interplay"*
    - 23-24 Nov *"2nd mini-workshop on FCC-ee detector requirements"*
    - 21-22 Nov *"Parton Radiation and Fragmentation from LHC to FCC-ee"*
    - 4-5 Feb *"10th FCC-ee physics workshop"*
    - 2-3 Feb FCC-ee Mini-Workshop: "*Physics Behind Precision*"
- **FCC-eh events**: http://lhec.web.cern.ch
- **FCC-hh events**: http://indico.cern.ch/category/5258/
  - Recent results: **"Physics at 100 TeV"**, Report, 5 chapters:
    - SM processes, arXiv:1607.01831
    - Higgs and EWSB studies, arXiv:1606.09408
    - BSM phenomena, arXiv:1606.00947
    - Heavy Ions at the FCC, arXiv:1605.01389
    - Physics opportunities with the FCC injectors, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

Reference literature

- **FCC-ee**:
  - "First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164
  - "High-precision α_s measurements from LHC to FCC-ee", arXiv:1512.05194
- **FCC-eh**: no document as yet, see however
  - "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector", J.Phys. G39 (2012) 075001
- **FCC-hh**: *"Physics at 100 TeV"*, Report, 5 chapters:
  - SM processes, arXiv:1607.01831
  - Higgs and EWSB studies, arXiv:1606.09408
  - BSM phenomena, arXiv:1606.00947
  - Heavy Ions at the FCC, arXiv:1605.01389
  - Physics opportunities with the FCC injectors, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

~700 pages

- **CEPC/SPPC**: Physics and Detectors pre-CDR completed, see:
  - http://cepc.ihep.ac.cn/preCDR/volume.html

See also:

- Physics Briefing Book to the European Strategy Group (ESG 2013)
- Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 3: Energy Frontier, arXiv:1401.6081
- N. Arkani-Hamed, T. Han, M. Mangano, and L.-T. Wang, Physics Opportunities of a 100 TeV pp Collider, arXiv:1511.06495

[No Title]

lepton collider parameters

parameter	FCC-ee (400 MHz)					LEP2
Physics working point	**Z**		**WW**	**ZH**	**tt_{bar}**	
energy/beam [GeV]	**45.6**		**80**	**120**	**175**	105
bunches/beam	30180	**91500**	**5260**	**780**	**81**	4
bunch spacing [ns]	7.5	**2.5**	**50**	**400**	**4000**	22000
bunch population [10^{11}]	1.0	**0.33**	**0.6**	**0.8**	**1.7**	4.2
beam current [mA]	1450	**1450**	**152**	**30**	**6.6**	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	**90**	**19**	**5.1**	**1.3**	0.0012
energy loss/turn [GeV]	0.03	**0.03**	**0.33**	**1.67**	**7.55**	3.34
synchrotron power [MW]	**100**					22
RF voltage [GV]	0.4	**0.2**	**0.8**	**3.0**	**10**	3.5

identical FCC-ee baseline optics for all energies

FCC-ee: 2 separate rings, LEP: single beam pipe

Operation plan

FCC-ee run	Z pole	WW threshold	HZ	$t\bar{t}$ threshold	Above $t\bar{t}$ threshold
$\sqrt{s}$ [GeV]	90	160	240	350	> 350
$\mathcal{L}$ [ab^{-1}/year]	88	15	3.5	1.0	1.0
Years of operation	0.3 / 2.5	1	3	0.5	3
Events	$10^{12}/10^{13}$	10^{8}	2×10^{6}	2.1×10^{5}	7.5×10^{4}

plus possible runs at the Z peak (125 GeV) and around the Z pole (extraction of α_{QED} at M_Z)

Hadron collider parameters

parameter	FCC-hh		HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		>25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		3.6	(0.35) 0.18

Operation plan

- **Phase 1 (baseline): 5 x 10^{34} $cm^{-2}s^{-1}$ (peak),**
  250 fb^{-1}/year (averaged)
  2500 fb^{-1} within 10 years (~HL LHC total luminosity)

- **Phase 2 (ultimate): ~2.5 x 10^{35} $cm^{-2}s^{-1}$ (peak),**
  1000 fb^{-1}/year (averaged)
  ➔ 15,000 fb^{-1} within 15 years

- **Yielding total luminosity O(20,000) fb^{-1} over ~25 years of operation**

FCC-he & HE-LHC-ep parameters

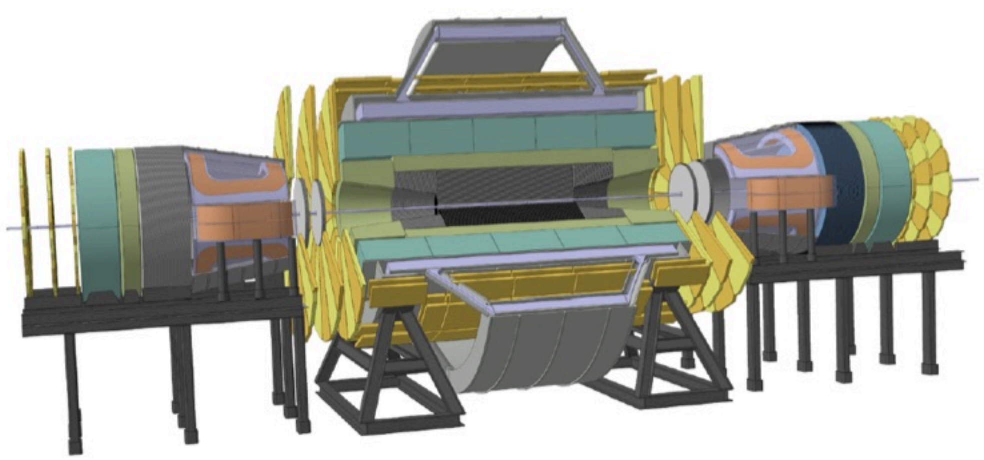
parameter	FCC-he	ep at HE-LHC	ep at HL-LHC	LHeC
E_p [TeV]	50	12.5	7	7
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	**3.5**	**1.7**	1.3	1.3
bunch spacing [ns]	25	25	25	25
protons / bunch [10^{11}]	1	2.5	2.2	1.7
$\gamma\varepsilon_p$ [μm]	2.2	2.5	2.0	3.75
electrons / bunch [10^9]	2.3	2.3	2.3	1.0
electron current [mA]	15	15	15	6.4
IP beta function β_p* [m]	15	10	7	10
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
proton-ring filling factor	0.8	0.8	0.8	0.8
luminosity [10^{33} cm^{-2}s^{-1}]	**11**	**9**	8	1.3

Reference detector

earlier design

6 T, 12 m bore solenoid, 10 Tm dipoles, shielding coil

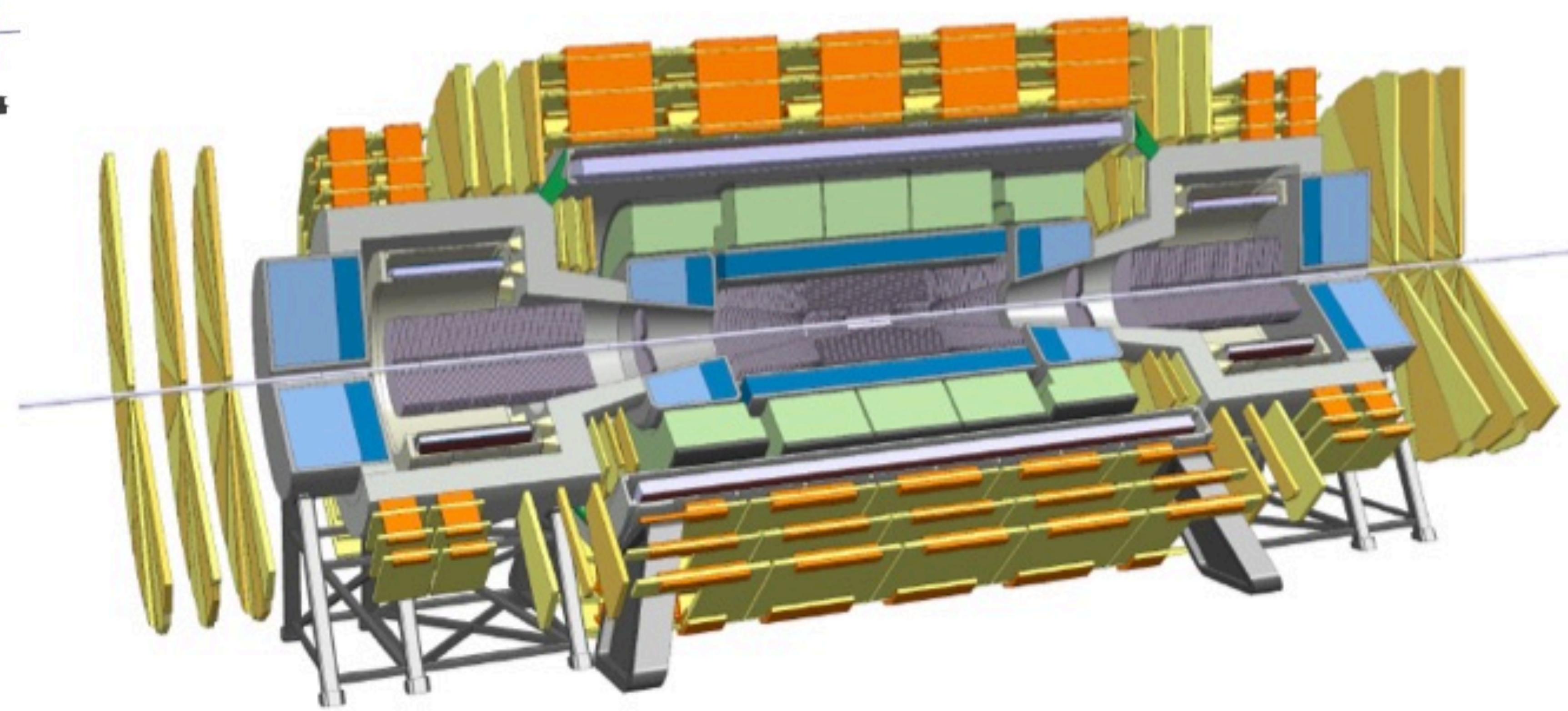
- 65 GJ stored energy
- 28 m diameter
- >30 m shaft
- multi billion project



current design

4 T, 10 m bore solenoid, 4 T forward solenoids, no shielding coil

- 14 GJ stored energy
- rotational symmetry for tracking!
- 20 m diameter (~ ATLAS)
- 15 m shaft
- ~1 billion project



latest l^* = 40 m

W. Riegler et al.

- **Detector design** group leader: Werner Riegler
  - Indico site of mtgs: http://indico.cern.ch/category/8920/
  - join the mailing list
- **Physics Simulation** subgroup leaders: Heather Gray & Filip Moortgat
  - Indico site of mtgs: http://indico.cern.ch/category/6067/
  - join the mailing list
- Monthly mtgs of each group, if interested register to the mailing lists